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Lubrication of
Industrial and
Marine Machinery

Lubrication of Industrial and Marine Machinery

SECOND EDITION

By the late WILLIAM GORDON FORBES

Revised by

C. L. POPE and W. T. EVERITT

NEW YORK · JOHN WILEY & SONS, INC.
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Preface

The purpose of this book is to provide a manual that may be used to explain the fundamental characteristics of conventional lubricants. Some of the more common basic mechanisms, such as bearings, gears, pumps, compressors, etc., have been explained in some detail. The integration of the lubrication principles with the lubrication requirements of mechanisms, as explained in this book, will enable one to solve lubrication problems.

Every effort has been made to present the various discussions with simple clarity, without using mathematical analysis and theories. It is our hope that this textbook will stimulate the student to further study in many of the phases that have been necessarily briefly covered. All engineering is a science that may be reduced to a mathematical analysis, and lubrication is fast becoming such a science.

An effort has been made to provide a logical sequence of study. The first fourteen chapters deal with the chemistry, refining, compounding, and specifications for lubricants. The second part, Chapters fifteen through thirty-two, explain the lubrication requirements of the most common types of machinery. The concluding chapters give practical examples of how the knowledge gained may be applied to the lubrication of equipment.

In revising this book of the late William Gordon Forbes, we have attempted to follow the scope and purpose of the original. Developments during the last nine years have necessitated the addition of new material and revision of some practices in the light of present knowledge.

In writing a book on such a wide subject as lubrication we have undoubtedly omitted many references to authors and sources of information. These omissions will be rectified if brought to the attention of the authors or publishers.

Rochester, N. Y.
January, 1954

W. T. Everitt
C. L. Pope

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1

Chemistry of Petroleum

Some knowledge of the chemical structure of petroleum lubricants is useful for understanding the application of lubricants. Yet the chemistry of petroleum is so complex and involved that only a general résumé will be given.

Atomic Structure of Hydrocarbons

All refined petroleum products, whether in the gas, liquid, or solid state, are primarily composed of only two elements, carbon and hydrogen; other constituents present in minor quantity, such as sulfur, are considered to be impurities. Hence, pure gasoline is composed of the same materials as pure lubricating oil. The fundamental difference between petroleum products is the arrangement and number of the individual carbon and hydrogen atoms which make up the particular type of molecules in the product. When two elements such as carbon and hydrogen combine to form another material, the resulting product is termed a chemical compound, and the smallest part of this compound is called a molecule. For example, water is a simple chemical compound wherein each molecule is composed of two hydrogen atoms and one oxygen atom. The atomic structure, or chemical formula, for water is written H_2O, which is a convenient abbreviation for two hydrogen atoms and one oxygen atom per molecule. In petroleum products, carbon and hydrogen atoms combine in various proportions to make a vast number of different products. The type of product depends upon the grouping of these atoms into molecules, and the pattern is termed atomic structure. In the following table the structures and individual boiling points are listed for a few products derived from natural gas and crude oil. Notice that, as the molecules increase in size, the gases become heavier until a point is reached where they become liquids at ordinary atmospheric temperature and pressure.

	Chemical Formula	*Boiling Point at Sea Level and Atmospheric Pressure*	
Gas	*per Molecule*	*°F*	*°C*
Methane	CH_4	−268.70	−161.5
Ethane	C_2H_6	−127.30	−88.5
Propane	C_3H_8	−43.96	−42.2
Isobutane *	C_4H_{10}	+10.22	−12.1
Butane	C_4H_{10}	+31.10	−0.5
Liquid			
Pentane	C_5H_{12}	97	36.1
Hexane	C_6H_{14}	156.2	69.0
Heptane	C_7H_{16}	209.3	98.4
Octane	C_8H_{18}	258	125.6

* See page 14.

Another interesting fact is that the great majority of petroleum products such as gasoline, fuel oils, and lubricating oils are composed of approximately 85 per cent carbon (C) and 15 per cent hydrogen (H) by weight. Not only is a product such as gasoline composed of the same elements as steam cylinder oil, but the proportions of carbon and hydrogen are the same. The difference between products is governed by the size of the molecules and the arrangement of the atoms in the molecules. It is this fact which makes possible the splitting of large molecules into smaller molecules to form gasoline and other light fractions by "cracking."

The commercial uses of these gases and liquids are many. Propane and butane may be mixed or sold separately in steel bottles for domestic fuel as well as for a fuel for internal-combustion engines. When sold in steel bottles these gases are compressed, become liquid, and remain liquid until released at the burner.

Butane, pentane, hexane, heptane, octane, etc., are all found in commercial gasoline. The presence of butane may seem extraordinary in view of its low boiling point. However, when blended with the heavier components, a small amount of this gas will remain as a liquid. Upon mixing with a large volume of air in the carburetor this type of highly volatile liquid instantly becomes a gas and makes starting of the motor much easier.

The atomic composition of heavier products such as lubricating oils is a more complex problem for the reason that molecule sizes and structures vary to a considerable extent. Lubricating oils are a mixture of molecules of different sizes and types which defy any simple formulas such as those listed. In fact, very little is known about their chemical structure. However, it may be assumed that lubricating oil molecules contain anywhere from 100 to 2000 atoms per molecule. Therefore, in order to follow the behavior of lubricating oils in practice, it is best to study the more simple atomic structures of the lighter products.

Changing Gases to Liquids

Just as the atmosphere is able to absorb and hold water in suspension, so petroleum gases are able to absorb various products and hold them in suspension.

One method commonly employed to separate the different products is that of compressing and cooling the gas. This method is based on the fact that a gas can contain only a fixed amount of liquid at a specified pressure and temperature (the dew point). In the case of sorting out gas products, this law is enforced by the simple process of compressing the gas and cooling it. For example, if the gas contains methane and pentane the volume of the gas may be reduced by compressors and held at room temperature by cooling coils. Under the altered conditions of reduced volume, there will not be sufficient room for the heavier product, pentane, to remain in suspension, and it will settle out as a liquid. If the gas is refrigerated the effect will be the same, only then the gas will automatically contract and throw down the heavier-bodied pentane in liquid form. In similar manner the air may be reduced in temperature and shrunk thereby until it can no longer hold any trace of water in suspension, and finally the air itself becomes liquid when the temperature reaches −214° F or −147° C. These various transitions are all linked up with the atomic construction of the particular molecule which types the resulting material, whether it be a gas, a liquid, or a solid.

Mechanics of the Atom

The elements in the universe, such as hydrogen, oxygen, carbon, tin, and gold, have been counted up to 92, which means there are 92 different types of atoms in existence. Several other elements, which are produced in atom smashing, are under investigation. Elements are the actual bricks from which everything in the universe is made, including life itself.

Atoms can be changed by extraordinary methods. Chemical combinations of atoms (molecules) may be changed to form new molecules, and the possible number of combinations runs up to astronomical figures. Even our present knowledge of chemistry has revealed more than 500,000 different carbon compounds. The investigation of this enormous profusion of compounds containing carbon is designated by a special classification in the field of chemistry, namely, organic chemistry.

Since atoms are among the smallest particles of matter in the universe, the elementary mechanics of their operation are of interest. The most popular and easiest way to visualize an atom is to consider its structure to be on the same plan as the little section of the universe upon which we live. In the center is a sun, and around the sun revolve several planets. The physicist has many terms for the parts that make up this amazing construction of atoms, but these theories and terms need not be discussed here. All atoms exist in this form, and the planets revolve around their suns at stellar velocities in their own tiny sphere. Even relative sizes and distances between the planets and suns in atoms are on the same scale as the stellar system in the universe. Strange as this may sound, chemists tell us that matter consists mostly of empty space, and if, for example, our bodies were compressed to a state of absolute solidity, the total mass would be smaller than an aspirin tablet. However, the weight would remain unaltered.

The application of heat causes atomic planets to swing around in wider orbits, and pressure results. If this action is made sufficiently violent on a gaseous petroleum compound, the original product may be changed into another product by the splitting up and division of the molecules. An example of this action is well illustrated in the cracking of light fuel or gas oil to secure more gasoline. In this case the violent action of heat and pressure on the hydrocarbon molecules causes them to split up into smaller molecules which in turn results in transforming part of the heavier fuel oil into gasoline. Up to 70 per cent gasoline may be secured in this manner from domestic fuel oil. By introducing a catalyst into this type of reaction the transformation is hastened and simplified, and for some operations superior results are secured at lower temperatures and pressures.

Catalysis

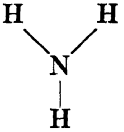
In many chemical combinations and changes involving the atoms of two or more elements, the desired changes and combinations may often be hastened by a medium known as a catalyst. The reason for this action is not understood, but catalysts appear to function very much like traffic directors. For example, if very fine coal dust and hydrogen gas are heated in a closed vessel very little reaction takes place, but when a catalyst such as platinum is hung in the vessel the coal dust will combine with the hydrogen gas to form crude oil. Since crude oil is composed of carbon and hydrogen, the artificial combination of coal dust (carbon) and hydrogen gas under conditions of heat, pressure, and time is to be expected. However, this action requires the presence of a catalyst to hasten the desired result, and even more curious is the fact that in the great majority of applications the catalyst remains unchanged throughout the process. When the catalyst tends to clog it has to be rejuvenated by washing off the material with a solvent or by fire. The layer need be only one molecule thick to make the catalyst inoperative. The type of catalyst best adapted to accelerate any particular chemical change is often a matter of painstaking trial and error, and, depending upon the particular process, the most desirable catalyst may be anything from platinum to clay. By displacing atoms in molecules and replacing them with others, the products obtained from petroleum are sometimes quite startling in their complete difference from the original. This is to be expected because even the human body contains catalysts in the form of iron, aluminum, etc., to produce the chemical reactions that are necessary to support life.

Valence

Most of the elements have an affinity for other elements and are capable of combining to form chemical compounds such as water, which is composed of oxygen and hydrogen. However, there are a few elements, such as the gases argon and neon, which will not combine with any other element, and their valence or combining power is therefore nil. However, the majority of elements will combine with one, two, three, or more other elements. For the purpose of simplicity in chemical studies, combining power with the gas hydrogen is used as a measuring stick to determine valence. This is not an exact definition but close enough to avoid complicated technicalities.

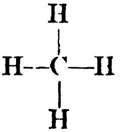
Therefore, valence may be reckoned as the maximum number of hydrogen atoms which another element can hold. For example, oxygen has a valence of 2 and when combined with hydrogen forms the molecule $H—O—H$, more conveniently written H_2O, which is one molecule of water.

Nitrogen has a valence of 3, which is drawn by the chemist thus:



or more conveniently NH_3, which is ammonia.

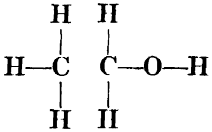
Carbon has a remarkable power of combining with hydrogen, nitrogen, oxygen, sulfur, and other elements to make up an almost unlimited number of materials. As mentioned previously, there are more than 500,000 known carbon compounds in the chemical catalogue. Carbon has a valence of 4, and the most simple hydrocarbon molecule is



$$\begin{array}{ccc} & H & \\ & | & \\ H - & C & - H \\ & | & \\ & H & \end{array}$$

or more conveniently CH_4, which is methane gas. However, under certain conditions carbon can have a valence of 2, such as carbon monoxide (CO).

Chemical combinations become more elaborate when the particular molecule is composed of several elements. For example, the formula for alcohol is CH_3CH_2OH. Notice that an atom of oxygen is present in this molecule. In diagrammatic form the arrangement of the atoms would be shown thus:



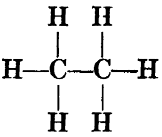
$$\begin{array}{cccc} & H & H & \\ & | & | & \\ H - & C & C & - O - H \\ & | & | & \\ & H & H & \end{array}$$

(one molecule of alcohol)

Notice also that if the atom of oxygen were eliminated from this molecule the product would change to ethane gas, something quite different from alcohol. The marvels of chemistry and of new chemical discoveries are all based on the arrangement of the atoms in a particular molecule. Life itself depends on the systematic arranging of various atoms to form various molecules, and the human body is an excellent example of a chemical factory which is far more complicated than any process found in the petroleum industry.

Saturated Hydrocarbons

This term is used to identify a particular family group of molecules which do not combine easily with other atoms or molecules. This is due to the fact that a saturated molecule is one that has all its valence bonds satisfied, and, holding hands, the atoms show no desire to let go. For example, the gas ethane is a saturated hydrocarbon wherein atoms of the little family are linked up in the form of a uniformly closed chain thus:

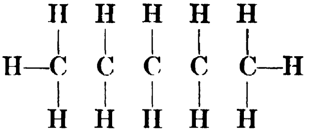


$$\mathrm{H{-}\underset{H}{\overset{H}{C}}{-}\underset{H}{\overset{H}{C}}{-}H}$$

Saturated hydrocarbons of this type are very stable and in lubricating oils they are highly resistant to change and to the formation of undesirable products. In chemistry this type of molecule is said to belong in the straight-chain series, and in petroleum chemistry they are termed paraffin molecules.

In reacting with other elements the straight-chain saturated hydrocarbons will not part with one or more atoms unless considerable force is used to pry them apart. This force has to be in the form of heat, pressure, the aid of a catalyst, contact with another chemically active element, or a combination of any of these forces.

Assuming the gas pentane



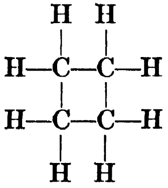
$$\mathrm{H{-}\underset{H}{\overset{H}{C}}\;\underset{H}{\overset{H}{C}}\;\underset{H}{\overset{H}{C}}\;\underset{H}{\overset{H}{C}}\;\underset{H}{\overset{H}{C}}{-}H}$$

(one molecule of pentane)

or C_5H_{12} to be brought into contact with the highly active element chlorine, a reaction might be effected to produce a new compound ($C_5H_{11}Cl$). Here one atom of hydrogen has been dislodged in each molecule and replaced by an atom of chlorine to form a new compound. This type of chemical change is termed "substitution," and the hydrocarbons of the chain group possess this characteristic in common. They comprise one of the largest family groups in the petroleum industry and exhibit the greatest amount of resistance to chemical change. Hence, saturated hydrocarbons are said to be highly stable, and crudes containing a high percentage of these molecules command the highest prices in the commercial markets, as for example, Pennsylvania and Mid-Continent crudes. However, a word of caution may be in order at this point, as the exact combination of various types of hydrocarbon and other molecules in lubricating oils is not known. For example, a lubricating oil containing nothing but one size and type of saturated hydrocarbon molecule would probably turn out to be a very disappointing achievement. Just as iron requires a combination of carbon and other metals to make it into alloy steel, so petroleum products require a combination of different molecules and constituents to make them into robust oils that are able to withstand the rigors of service in engines and machines. Without these other aids, the imaginary perfect oil might not lubricate the bearings of a sewing machine.

The practical advantage of having a preponderance of saturated hydrocarbons in petroleum products is illustrated in a number of ways. In kerosene they burn cleanly and leave very little carbon on lamp wicks. In the cylinders of Diesel engines, where high temperatures and pressures are encountered during combustion, the higher the percentage of saturated hydrocarbons in the fuel oil the cleaner the burning properties and the less trouble from products of decomposition, particularly gummy and carbonaceous deposits which form in the cylinders and between the piston rings. Saturated hydrocarbons are highly desirable in gasoline for aircraft engines on account of their stable properties under all manner of conditions; this feature is particularly important in eliminating the danger of hard, gummy, or varnish-like products of decomposition which tend to lodge on valve stems, piston ring grooves, and in the carburetor and gasoline lines. In engine-circulating oils saturated hydrocarbons are desirable on account of their ability to resist "sludging." In steam-cylinder oils they are desirable on account of their resistance to decomposition and the tendency to form deposits at elevated temperatures, particularly when superheated steam is used to operate the engines.

Another important family group of saturated hydrocarbons is the naphthenic series, wherein the atoms are arranged in ring form:



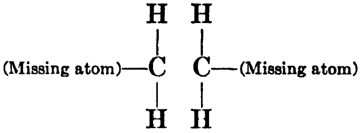
or C_4H_8

(cyclobutane)

The naphthenic groups are not quite as stable as the paraffin or straight-chain hydrocarbons, and the boiling points are generally lower. Nevertheless, the ring groups are very important, and in lubricating oils these two types, paraffin and naphthene, are by far the most important. All lubricating oils contain both types, the proportions depending upon the source of the original crude. As a general rule, the more asphalt in the original crude, the more naphthenic the structure of the products obtained.

Unsaturated Hydrocarbons

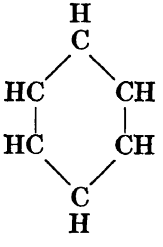
When petroleum was manufactured by a process of nature under the ground, there appears to have been a shortage of hydrogen. As a result of this shortage, a small percentage of hydrocarbon molecules exist without their full quota of hydrogen atoms, and they are termed "unsaturated hydrocarbons." Unsaturated molecules are unstable for the reason that they are ready at the first opportunity to satisfy their appetite on any digestible atoms with which they may come in contact. Every motorist knows what crankcase sludge looks like, a substance which is brought about by unstable hydrocarbons digesting oxygen from the air and changing to a product which is no longer lubricating oil. In diagrammatic form, an unsaturated hydrocarbon might be illustrated like this:



$$\text{(Missing atom)}-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}\quad\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-\text{(Missing atom)}$$

In this form the valence bonds of the molecule are not satisfied; there are two hydrogen atoms missing in the chain to make a complete molecule, and the two vacant places are ready to hook onto any other atoms which will fit into the atomic structure or pattern.

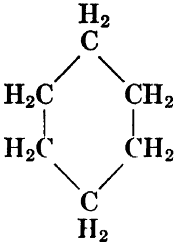
Other types of unsaturated hydrocarbon molecules are numerous, as for example those known as aromatics. The molecules in this group are also arranged in rings:



or C_6H_6
(benzol)

Conversion: Unsaturates to Saturates

Many aromatic-type products, incidentally, have a pleasant odor, hence the name "aromatic." Aromatic-type compounds such as benzol are fairly stable under atmospheric conditions, but they are nevertheless unsaturated and therefore reactive. Hence, by adding hydrogen, benzol becomes hexahydrobenzene, which is a saturated hydrocarbon of the naphthene or ring class.



or C_6H_{12}
(hexahydrobenzene)

Principal Types of Petroleum Molecules

From these examples of subtracting and adding to molecules it is not hard to understand the ramifications of the petroleum industry. Most of the products of the cracking process are entirely different from anything found in nature. The greater the number of carbon atoms in the molecule, the greater the possibilities of splitting it into smaller sections and varying its structure. The four principal types of molecular construction which the chemist has to deal with are straight chain (paraffin), ring (naphthene), aromatic, and unsaturates. The first two types are saturated, and the last two are unsaturated. There are of course many other types, such as part chain, part ring, branched chain, etc., some of which are extremely complicated in structure. For the purpose of manufacturing synthetic products, large quantities of unsaturated hydrocarbons are produced by "cracking."

Other Compounds

Other types of compounds found in small quantities in crude petroleum are generally classified as impurities. Most of these are removed and processed and eventually find useful applications. Others of a harmless nature may be left in the finished product, depending upon its commercial use. For example, most lubricating oils contain a small percentage of natural sulfur compounds, which are the largest family group of impurities.

Thermal Cracking

This process is commonly carried out on gas oils, light fuel oils, etc., but it may be carried out on heavier or lighter products, depending upon the type of crude, the ease with which it will crack, or the market demands for particular petroleum products.

Thermal cracking is commonly done by heating the liquid and holding it under pressure until the molecules have been torn apart. During this process of rearrangement the larger molecules split up into smaller molecules, and, since there is not enough hydrogen to balance or saturate the new molecules, most of them are left unsaturated. However, another reaction which takes place is a merger of some of the new molecules with each other. The final result is that every molecule is changed, some only slightly, but others to a considerable extent.

Much of the cracked distillate is used as basic material for separate industries, while as much as 70 per cent of some charging stocks may be transformed into gasoline with installations adapted to crack for the maximum percentage of gasoline.

There are several types of cracking plants, but the physical principles of operation are similar in all.

The cracking of gas oils produces two principal types of hydrocarbons, aromatic and unsaturated. The aromatic or ring types are fairly stable, and when the cracked distillate has been redistilled the aromatic gasoline secured thereby is blended with straight-run gasoline. Owing to the fact that light aromatic-type hydrocarbons have slower burning properties under pressure, they are blended with straight-run gasoline to improve the antiknock qualities of the finished blend.

On the other hand, aromatic or cracked fuel oils have to be blended with straight-run fuel oil rather sparingly for the reason that aromatics tend to impair the burning qualities of fuel oil, particularly in Diesel engine cylinders. When too much cracked fuel oil is blended with straight-run fuel oil, there is also a tendency to set up a solvent refining action which throws down a soapy type of sludge in storage tanks. Hence blending is carried out sparingly to prevent these troubles and still not to impair the stability of the fuel oil. In heavy grades, such as bunker fuel oil secured in the cracking process, no blending or thinning is permissible with straight-run fuel oils for the reason that a definite solvent refining action takes places on the heavy fuel oil, and an asphaltic type of sludge is thrown down in appreciable quantity as a result of this action.

The unsaturated hydrocarbon distillates secured in the cracking process are transformed by synthetic manufacturing methods into saturated hydrocarbons by promoting chemical unions with other atoms. Unsaturated hydrocarbon distillates are used to make a variety of chemicals by causing them to absorb other elements to form new products which range from poison gases, anesthetics, explosives, and antifreeze compounds to synthetic rubber, etc.

The great importance and obvious advantage of low temperatures and high gas velocities in the original distillation process are well illustrated by considering the effect of cracking. In fact, petroleum products are very often subjected to some form of cracking effect when placed in commercial use, as for example in the cylinders of internal-combustion engines or, at a slower rate, in circulating oiling systems, etc., particularly where heat or some form of metal catalyst is present to accelerate the action.

After a product such as gas oil has been subjected to the cracking process the condensed liquids are redistilled and the various products separated in fractionating towers, where the cuts or fractions are drawn off in the manner described in Chapter 2.

Catalytic Cracking

Catalytic cracking is also employed extensively. By the use of a catalyst it is possible to control the cracking process to produce gasoline with antiknock and stability qualities superior to those obtained by thermal cracking. Catalytically cracked gasolines processed by controlled synthetic means contain relatively high percentages of saturated hydrocarbons. Hence, this method is advantageous when the main object is to crack for gasoline.

Each cracking operation is a separate study, and much depends upon the source and composition of the crude. Sometimes considerable research work is necessary before a decision can be made about the type of equipment, type of catalyst, and other details best adapted to carry out a particular cracking operation.

Reforming

This is also a cracking process which is sometimes carried out on gasoline to improve its antiknock properties. By subjecting straight-run gasoline to the cracking action of heat and pressure, the percentage of aromatic- or ring-type molecules is increased. However, this type of gasoline can be used only sparingly in motor fuel and not at all in aircraft-engine gasoline on account of its tendency to form gum. This process is being replaced by more recent developments comprising catalytic actions wherein the temperatures are lower and the action less violent. As a result, the percentage of unsaturated hydrocarbons is much lower and a more stable product is secured.

Hydrogenation

The process of adding hydrogen to unsaturated hydrocarbons, known as hydrogenation, opens the door to other industries, such as combining pulverized coal and hydrogen gas to produce synthetic crude oil.

From the process known as cracking, wherein the molecules of gas oils and similar distillates are shattered and torn apart, springs the commercial supply of unsaturated hydrocarbons. This source forms the basis of industries wherein new materials are produced from petroleum by filling the vacant places of stripped molecules with hydrogen atoms.

Polymerization

Hydrogenation means adding hydrogen to unsaturated hydrocarbons. Polymerization is any process that will combine unsaturated molecules with each other to form a larger molecule. For example, propylene is a gas at atmospheric pressure and temperature, but, with the aid of heat and a catalyst, propylene can be made to combine with propylene to double the size of the molecule and to make a heavier product, which is liquid at atmospheric pressure. Thus, the molecules become saturated and the resultant liquid may be used in gasoline. By a combination of hydrogenation and polymerization a great variety of commercial products are made from unsaturated hydrocarbons produced in the cracking process. For example, isoöctane is made this way and is extensively blended with straight-run gasoline to make aircraft gasoline. Isoöctane has slower burning qualities under heat and pressure, and it aids in eliminating "knock" in gasoline engines. Toluene is another of the products made by synthetic methods. This liquid is a solvent and is extensively used in explosives such as TNT (trinitrotoluol).

Alkylation

Alkylation is similar to polymerization, but it involves the combining of unsaturated molecules with saturated molecules. For example, this process is employed to manufacture isoöctane, isopentane, cumene, triptane, and similar high-antiknock-value fuels for gasoline engines. One method of carrying out the operation is to mix the unsaturated hydrocarbon gas butylene with the saturated hydrocarbon gas isobutane in a tank containing sulfuric acid. The sulfuric acid acts as a catalyst to combine these gases and to produce a new gas termed "diisobutylene." This latter gas is then mixed with hydrogen gas in the presence of another catalyst, and with the aid of heat the diisobutylene absorbs hydrogen and the transformation to isoöctane is effected.

Isomerism

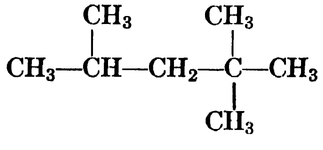
The term "iso" means branched chain, and in refinery practice the process of isomerization means changing straight-chain molecules to branch-chain molecules for the purpose of improving the burning or antiknock properties of fuels.

The term "isomerism" is used to describe a peculiar characteristic wherein two products may have the same chemical formula but vary in certain physical ways.

One of the most striking examples of isomerism is shown by the particular hydrocarbon liquid known as octane. Normal octane secured by straight distillation of petroleum crude has only average antiknock value when burned in the cylinders of a gasoline engine. On the other hand, isoöctane secured by synthetic methods has a very high antiknock value and is rated 100 for this particular property. However, both products have the same chemical formula. The molecular arrangement for normal octane of a normal paraffin-type or straight-chain molecule found in straight-run gasoline is:

$$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3 \quad (\text{or } C_8H_{18})$$

The molecular arrangement for isoöctane is a branched chain:



$$CH_3-\overset{\displaystyle CH_3}{\overset{|}{C}}H-CH_2-\overset{\displaystyle CH_3}{\overset{|}{\underset{\displaystyle CH_3}{\underset{|}{C}}}}-CH_3 \quad (\text{or again } C_8H_{18})$$

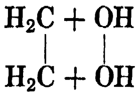
Aromatization

This is another process for changing hydrocarbon molecules into branch-chain and aromatic molecules to obtain such products as cumene, a rich mixture agent which gives a "lift" to aviation gasoline.

Toluene, an important industrial solvent, as well as many others such as "styrene," used in making synthetic rubber, can be made this way.

Other Examples of Synthetic Manufacturing

Ethylene (C_2H_4) is a light gas secured in commercial volume from the cracking process, and, being unsaturated, it may be made into many products such as glycol, which is similar in structure to glycerine secured from animal fats. The addition of oxygen and hydrogen to ethylene produces the reaction of



$$\begin{array}{ccc} H_2C & + & OH \\ | & & | \\ H_2C & + & OH \end{array}$$

(one molecule of ethylene glycol)

a heavy-bodied liquid which mixes easily with water and is used for lowering the freezing point of water in automobile radiators, for the liquid cooling of aircraft-engine cylinders, and so on.

Another product made from ethylene is nitroglycol, a powerful explosive with properties similar to those of nitroglycerine. Many more products can be manufactured from ethylene by simply building up the atomic structure of the original molecule, and many more gases and liquids secured from the cracking process may be made into different products by adding various elements. For example, rubber, anesthetics, etc., are manufactured this way.

2

Distillation

Composition of Crudes

Crude oil is commercially sorted into various products termed "cuts" or "fractions" by the simple process of boiling and then condensing the vapors. The following chart gives some idea of the composition, in per cent, of crudes from various sources.

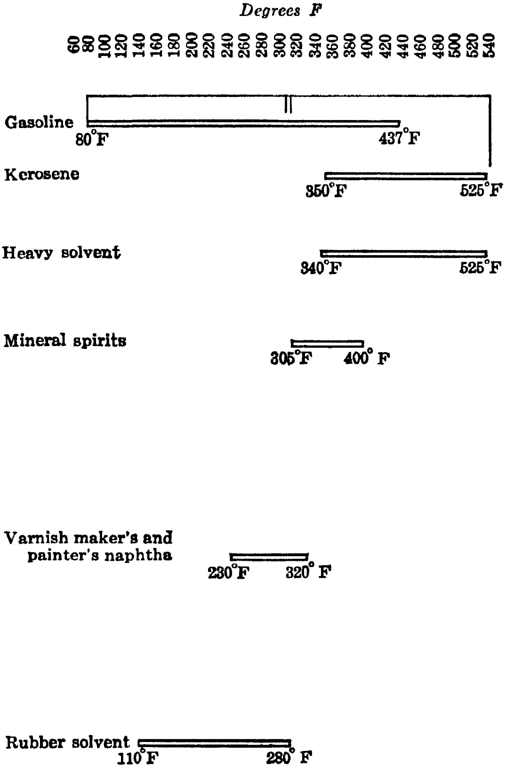
	Pennsylvania	*Mid-Continent*		*Texas*		*West Coast*	
Gasoline	35	35	30	30	5	30	25
Kerosene	15	10	10	5		10	..
Gas oil	20	25	40	35	50	30	20
Lubricating oil	30	25	10	15	10	20	..
Asphalt	..	5	10	15	35	10	55
	100	100	100	100	100	100	100

These estimates are very rough and show merely the great variance of crudes from different fields. In fact, no two oil pools give exactly the same type of crude, and the process of cracking would alter the percentages of the final products in any of the above estimates.

Unlike water, which boils uniformly at 212° F under atmospheric pressure at sea level, crude oil contains a variety of materials, and each commercial product generally has a *range* of boiling points because it contains a mixture of hydrocarbon compounds, each group having a different but individual boiling point. For example, the initial boiling point for gasoline of average commercial grade is about 90° F, and the final boiling point is about 400° F. In Fig. 1*A* the initial and final boiling points of a few well-known commercial petroleum products are outlined. Notice that in some cases the cuts or fractions could be secured from commercial gasoline by redistilling and controlling the initial and final boiling points as designated. Any of the liquids which have a narrow range, such as paint thinner, could be made in the simple apparatus shown in Fig. 1*B*.

When handled separately, each of the hydrocarbons present in crude oil behaves in the same way as water, but since they are never produced by nature separately, the products made from crude oil rarely consist of single components. In refinery practice we are principally concerned with mixtures containing a variety of hydrocarbons.

BOILING RANGES OF SPECIAL PRODUCTS IN
COMPARISON WITH THOSE OF GASOLINE AND KEROSENE



Commercial Uses of Special Products

Engine fuel.

Lamps, cleaning.

Soap manufacture, heavy naphtha, insecticide base.

Thinner for paint and varnish, polishes, liquid wax. Turpentine substitute. Washing parts to be painted. Solvent for dry cleaning and safety solvent for household use.

Used instead of mineral spirits where quick drying is required. Solvent for dry cleaning where driers or tumblers are not used. Domestic dry-cleaning naphtha.

Manufacture of rubber cement; tires, tubes, brake linings; quick-drying paints, stains, etc.

FIG. 1A.

Preliminary Distillation of Crudes (Steam Distillation)

When steam is continuously blown into crude oil in a still, steam vapors are mixed with oil vapors so that the total pressure is obtained from both together. Thus, when the joint pressures are equal to, or above, the atmospheric pressure, the oil, having to supply only a part of the pressure, boils at a lower temperature.

For example, when alcohol is added to the water in a radiator to prevent freezing, the boiling point of the mixture is lowered. The boiling point of water is 212° F, and that of alcohol 142° F. Hence the new boiling point will be somewhere between these two limits. When the mixture does boil, the vapor will contain a high percentage of alcohol as well as some of the less volatile water. As evaporation proceeds, the boiling point of the remaining liquid will rise. Thus, for such a mixture there is no boiling temperature; it is a boiling range.

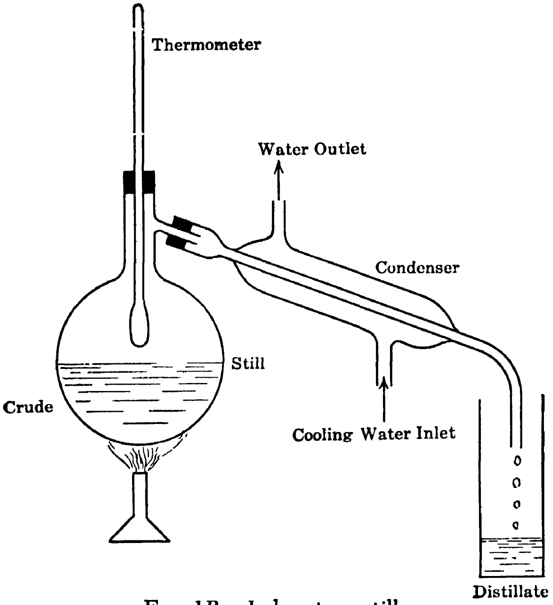


FIG. 1*B*. Laboratory still.

This phenomenon is very pronounced for petroleum products, as they consist of many components. The boiling temperature will rise continuously from the initial boiling point (I.B.P.), up to the final temperature when the last drop of liquid evaporates, known as the final boiling point (F.B.P.). Within the boiling range of gasoline there are nearly 6000 possible hydrocarbons, and each individual group has a different boiling temperature.

In commercial practice, crude oil is distilled in fractionating towers which operate continuously. Figure 2 shows the basic operating principle of a fractionating tower, and Fig. 3 shows the construction and operation in more detail. Crude oil is preheated and continuously pumped into the tower at the approximate level shown. Heat within the tower is applied by means of steam jets directly streaming into the charge of crude oil, whereupon the crude begins to boil and vapors rise in the tower. At each step, the vapors are forced to pass through bubble caps which are arranged on trays as shown in Fig. 3, and before these vapors can reach a higher level, they are forced through the liquid which has condensed on that particular tray. As a result of this continuous condensing action, only the lightest vapors reach the top of the tower. From there they pass along to coolers where the heavier fractions are condensed and become raw gasoline. After treatment with various simple chemicals to remove excess sulfur and other unwanted or objectionable foreign compounds, the raw gasoline is ready for blending and transforming into a commercial product. The very light gases, which do not condense at ordinary climatic temperatures and pressures, are generally transferred to synthetic manufacturing divisions of the refinery or compressed in steel bottles for domestic burner use.

The remaining vapors condense into liquids within the tower, and at the approximate levels shown these liquids are continuously drawn off from the trays. The lighter and more volatile liquids condense nearest the top of the tower and the progressively heavier ones toward the bottom of the tower. Those liquids which refuse to boil at the fractionating temperatures remain in the lower section of the tower and are drawn off at the bottom. When the original charging stock is of the type that yields lubricating oils, or asphalts, this residue forms the first step in securing the material from which these products are manufactured.

The first refining operation performed on crude oil is termed "topping" for the reason that, as shown in Fig. 2, the tower tops off the lighter and more volatile products such as gasoline, kerosene, the lighter-bodied fuel oils (gas oil), down possibly to the lighter-bodied lubricating oils.

In refining operations the term "gas oil" is used to denote the liquid which has a boiling range between that of kerosene and light lubricating oils. For example, domestic burner and Diesel engine fuels are derived from this cut. The term "gas oil" is a convenient designation for a wide range of comparatively light-bodied distillates lumped together. Gas oils range widely in color, depending upon the source of the crude, from light straw to opaque black. The initial boiling point

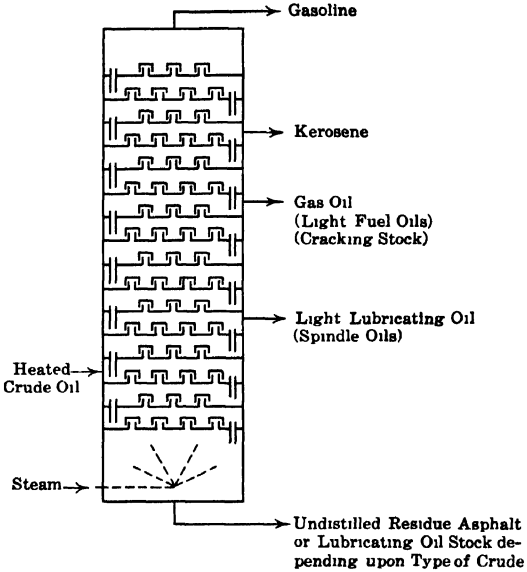


FIG 2 Diagrammatic cross section of a fractionating tower

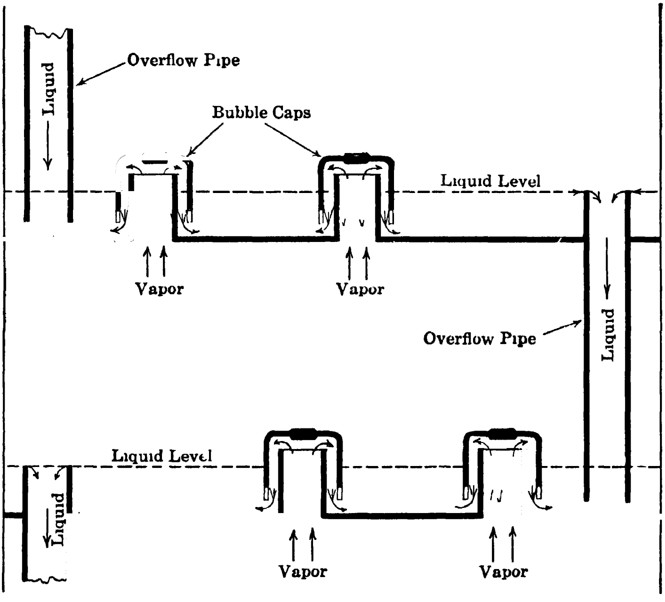


FIG 3 Trays and bubble caps inside fractionating tower Diagram shows the liquid levels and the upward path of the vapors

for an average gas oil is about 375° F and the final boiling point about 750° F. The most valuable gas oils, insofar as wide commercial use is concerned, are those which easily give burner and Diesel engine fuels. Some of these products may be run off direct from the tower and sold in the commercial market. Others require redistillation and chemical treatment before they can be considered commercial products. Very often this cut is transferred to the cracking process to secure more gasoline, or it may be cracked to secure base stocks for making synthetic products.

In a fractionating tower the temperatures at the top and bottom are carefully controlled by instruments to secure uniform fractions from the outlets. In similar manner the temperature and volume of the incoming crude oil is controlled by instruments. The entire operation is automatic and is precisely balanced at every point. However, in actual practice, each tray tends to collect a liquid with a rather wide boiling range and, in order to narrow this boiling range and eliminate the necessity of redistilling the lighter fractions, the practice of "side stripping" is generally employed. (See Fig. 4.)

Side strippers are a component part of the fractionating tower, and they are of similar construction. At selected points, liquid is drawn from the trays and run into the side strippers where it flows downward through bubble caps and trays but meets a flow of hot steam rising upward. The steam boils off the lighter vapors and thus narrows the boiling range of the remaining liquid in the stripper. The vapors thus boiled off, together with the steam, are automatically returned to the fractionating tower. By the use of two or more side strippers operating in conjunction with the main tower, continuous streams of gasoline vapors, liquid kerosene, and light fuel oils are obtained without further resort to redistillation. Near the top of the main tower, the vapor temperature is controlled by pumping back part of the condensed gasoline. This particular distillate is termed "reflux," and the operation is a convenient method of controlling the final boiling point of the gasoline vapors leaving the top of the tower. Without this governing factor some vapors would pass over which would be too heavy to meet the gasoline specification and would rightfully belong in kerosene or the less volatile fractions.

Variations in fractionating operations are of course numerous and depend upon the type of crude oil that is being distilled. When the refinery is called upon to handle a new type of crude, distillation tests are made in the laboratory to determine the most suitable fractionating methods. The results of these tests, including all pertinent data, are turned over to the operating personnel, who plan their operations accordingly. No refinery is equipped to handle every type of crude oil from the raw state to all the finished products it may contain. Residues are often sold to other refiners, as for example asphaltic residues, which are worked up by refineries specializing in the manufacture and sale of asphalt.

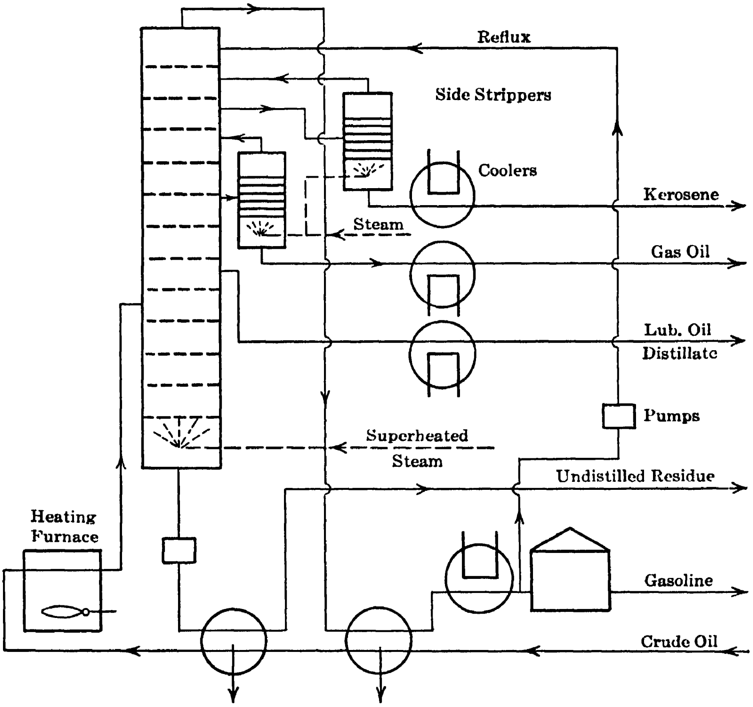


FIG. 4. Flow diagram of distillation tower showing side strippers.

Assuming the charging stock to be a high-grade crude containing approximately 35 per cent gasoline, 15 per cent kerosene, 20 per cent fuel oil, and 30 per cent lubricating oil, the charging stock would possibly enter the tower at about 650° F. The temperature at the bottom would be about 450° F, and the temperature at the top about 320° F. The approximate speed of the vapors rising in the tower would be about 80 miles per hour. When the charging stock is composed of heavy asphaltic material, or is a paraffin type of crude containing a preponderance of liquids of high boiling point, the temperature of the incoming crude oil would probably be higher, possibly 700° F.

In refining operations, considerable use is made of heat exchangers which utilize heat that would otherwise be wasted. Figure 5 shows the construction of a heat exchanger. Hot liquid is pumped through the tubes while cooler liquid passes over the outside of the tubes. For example, if cold charging stock is pumped over the tubes and hot liquid from the tower pumped through the tubes, a convenient exchange of heat takes place.

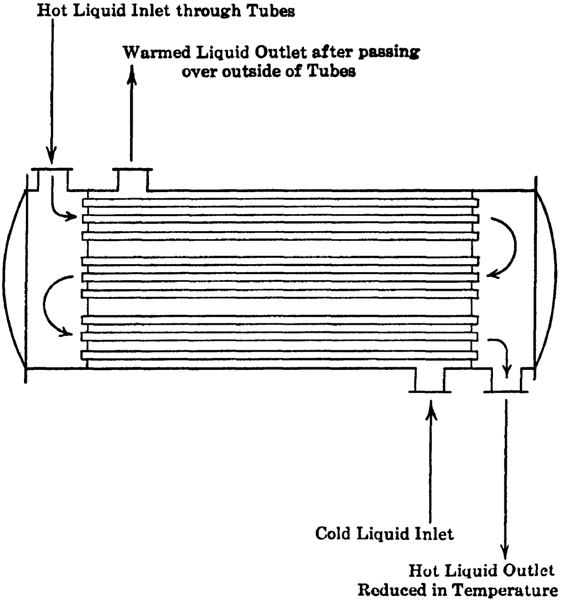

Hot Liquid Inlet through Tubes
Warmed Liquid Outlet after passing over outside of Tubes
Cold Liquid Inlet
Hot Liquid Outlet Reduced in Temperature

FIG. 5. Diagram of heat exchanger. This type of unit may also be termed a cooler or a condenser, depending upon the service.

These and other details, such as eliminating condensed steam from the liquids, are all part of the distillation process. Condensed steam or water will separate almost instantly from such products as gasoline, kerosene, and fuel oils, and the largest towers can be operated by a few men located at the key points of control.

In the majority of refining operations the residues which remain after the topping operation contain the basic materials from which other products are secured. In working up these residues, much depends upon the type of crude and to some extent upon the prevailing market requirements for petroleum products. For example, the residue may be light enough to market as fuel oil, or it may be very heavy and have a high asphaltic content, in which case it becomes road-making material, etc. Residues are entirely governed by the source and nature of the crude; in this textbook only those residues which contain lubricating oils are of special interest. In the lighter fractions, modern cracking and catalytic processes are capable of splitting one fraction into another with comparative ease, but the scope of this book is not wide enough to permit all the details of these interesting transformations.

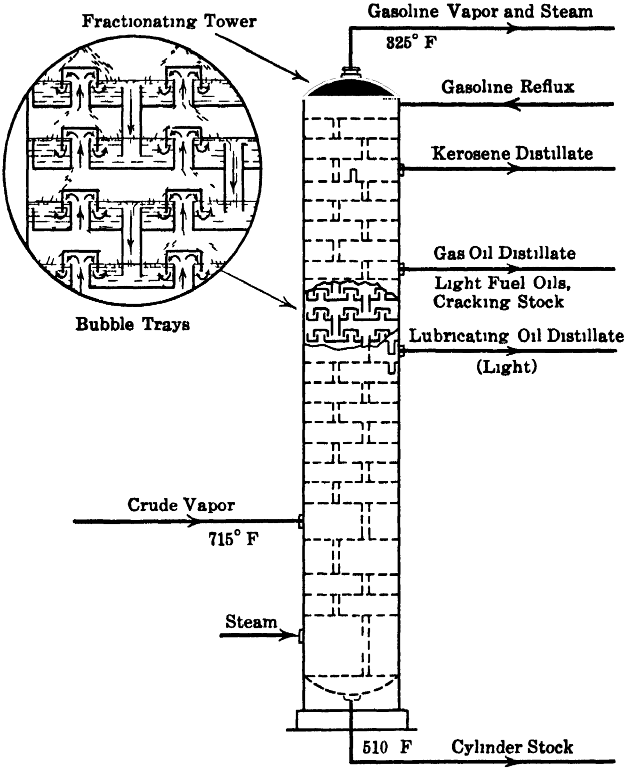


FIG. 6. General outline of refinery for Pennsylvania type crude.

Before leaving the subject of crude-oil distillation the reader should also study Fig. 6, which shows the flow diagram and general outline of a plant refining high-grade Pennsylvania crudes. Notice that in this particular operation several cuts are run off from the fractionating tower for the reason that the tower and all the external details have been designed to handle this type of crude.

3

Distillation of Lubricating Oils

Light lubricating oils are distilled in the same manner as gasoline, kerosene, light fuel oils, etc. The only difference is that sometimes a vacuum is maintained at the top of the fractionating tower to keep the distilling temperatures as low as possible (see Fig. 1). This arrangement lowers the boiling points of the liquids and thereby prevents damage or cracking of the molecules.

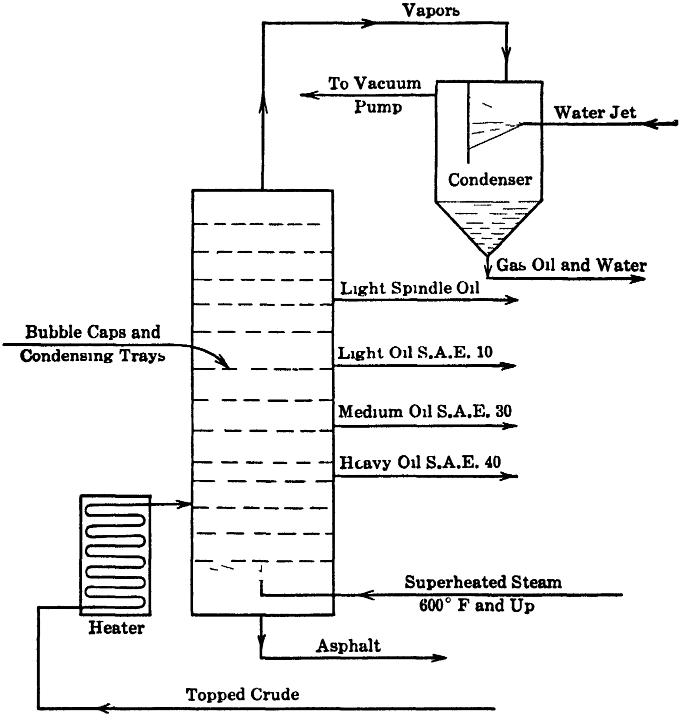


FIG. 1. Vacuum distillation of lubricating oils from asphaltic-base charging stock.

This method is based on the fact that the lower the pressure above a liquid, the lower the boiling point. For example, in a high vacuum, water will boil at 70° F, whereas under atmospheric pressure at sea level water boils at 212° F. Hence the same effect takes place in the process of vacuum distillation, and, in distilling lubricating oil residues, destructive temperatures are held down to a minimum. The vacuum is maintained by rapid condensation and consequent contraction of the light vapors which are brought into direct contact with a spray of cold water in a condensing vessel, and the vacuum is further maintained or augmented by suction pumps drawing off stray vapors which collect in the condensing vessel.

In a modern vacuum-distilling plant operating under a high vacuum, the average temperatures within the tower may be 100° to 300° F below those in a tower operating without a vacuum. The vacuum at the top of the tower is generally maintained at about 1 pound pressure absolute, while the pressure within the condensing vessel is generally about ½ pound absolute. The term "absolute" is a reference to a complete state of vacuum; for example, 1 pound absolute means a pressure of 1 pound per square inch above an absolute vacuum.

Theoretically, the vacuum process is very desirable for securing lubricating oil fractions, but to maintain a vacuum the volume of vapor is correspondingly high, and therefore difficult to handle. For this reason the vacuum process is not always used, and high-speed distillation under atmospheric pressure is relied upon to prevent decomposition or cracking of the products. This is an important factor in preventing decomposition since, if the vapors are forced to move rapidly, there is little time to injure the products.

In the distilling operation charging stock or topped crude, from which gasoline, kerosene, and light fuel oil have been extracted by previous distillation, enters a heater and passes into the tower. This tower is generally between 80 to 100 feet in height, and the entering stock is introduced at a point 15 to 20 feet from the bottom.

The tower is constructed with trays and bubble caps in the same manner as shown and described in Chapter 2. Superheated steam comes into direct contact with the charging stock, and the condensed oil vapors are drawn off particular trays at various levels all the way up the tower. Those vapors which condense near the top of the tower are light lubricating oil fractions, and at the bottom the unvaporized portion may be asphalt or heavy-bodied lubricating oil (cylinder stock), depending upon the character of the original crude.

The oil fractions drawn off at the various outlets are termed "neutrals," and their viscosity or body is designated by the figures 100, 250, 500, etc. These figures indicate the Saybolt viscosity reading of the particular fraction. For example, a 250 neutral simply means that the oil has a viscosity of 250 seconds at 100° F when tested in the Saybolt viscometer.

When the liquid at the bottom of the tower is classified as "steam-refined stock" the product is a heavy viscous lubricating oil which will not boil at the prevailing temperatures within the tower. The viscosity of steam-refined stock is taken at 210° F, and this fraction is the basic material for steam cylinder oils, gear oils, etc., and is even more extensively used for blending with lighter oils.

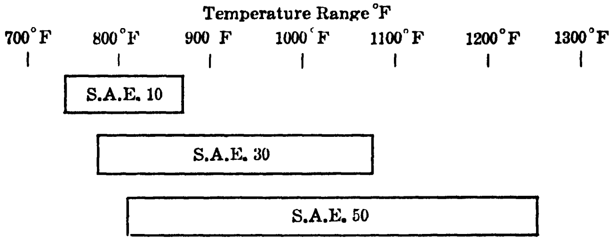


FIG. 2. Approximate boiling range of three Pennsylvania motor oils under atmospheric pressure. Final residues of carbon material not taken into account.

The design of a fractionating tower and the number of outlets depend upon the original source of crude. For example, high-grade Pennsylvania charging stocks are generally drawn off at two points only; the light fraction is distilled off and is termed a light neutral (150 to 180 seconds Saybolt viscosity at 100° F), and the other, which remains undistilled, is drawn off the bottom. This is known as steam-refined cylinder stock (generally 125 to 300 seconds Saybolt viscosity at 210° F). From these two fractions high-grade Pennsylvania motor oils are made by blending the light oil with the more viscous cylinder stocks in various proportions. The reason for this procedure is that Pennsylvania charging stocks would require destructive temperatures to vaporize intermediate oil fractions. The molecules are of the distinctive chain type of paraffin series which have very high boiling points (see Fig. 2).

The methods used for distilling the majority of Mid-Continent charging stocks are very similar to the methods used for Pennsylvania charging stocks. The lubricating oil fractions are generally 100 neutral, 250 neutral, and undistilled cylinder stock from the bottom of the tower.

The liquids of the naphthenic types of charging stocks, such as the stocks derived from many Texas, Gulf Coast, and California crudes, have lower boiling points and therefore vaporize at lower temperatures. The lubricating oil stocks may thus be distilled and drawn off from the tower at several points to give a range of different-bodied oils. When the charging stock is sufficiently naphthenic in molecular structure, the oils may be drawn off direct from the tower to meet the viscosity specifications of various commercial motor oils. Later, of course, they are further refined to eliminate asphalt, objectionable compounds, wax, etc.

The fractionating procedure for a particular charging stock depends entirely upon the predominating molecular construction of the original crude. Crudes of the paraffin type have the highest boiling points; next comes "mixed base" or paraffin-naphthenic type, while those with the lowest boiling points are naphthenic base crudes. The great majority of lubricating oils are manufactured from mixed-base crudes.

As a general rule, the more asphalt in the original crude, the more naphthenic the type of molecules in the lubricating oil. Hence the term "asphaltic base" is sometimes applied to lubricating oils which have been refined from crudes containing a comparatively high percentage of asphalt.

The specific gravity of a lubricating oil was formerly a guide to determining the type of crude from which the oil was manufactured, but with improvements in refining methods this is no longer a definite classification. However, it is generally true that when two lubricating oils have about the same viscosity, the oil with the lower specific gravity will contain the highest percentage of paraffin-type molecules; but even this type of comparison is no longer a measuring stick in determining the suitability of a lubricating oil for a particular purpose.

Gravity readings are an important detail in the distilling process for the reason that they indicate divisions of fractions. For example, if the stillman should notice a change in gravity at a particular outlet he knows immediately that an unwanted lighter or heavier fraction is condensing on the trays in that section of the tower, and the temperature must be adjusted inside the tower to correct the particular fraction.

Classification of Mineral Oils by Source of Crude

The terms employed to describe the basic types of mineral oils are rather loose and arbitrary. There is no exact line of demarkation between a paraffin-base oil, a mixed-base oil, and a naphthenic- or asphaltic-base oil. One way of distinguishing one type from another is by the physical tests for gravity (A.P.I.), flash point, and viscosity index. The paraffin-base stocks register the highest readings for these three values. Hence, the lower these readings, the more naphthenic the molecular structure of the oil.

As a general rule, paraffin-base lubricating oils are blends of light distillates and heavy undistilled stocks, whereas the naphthenic- or asphaltic-base oils may be run directly from the distilling process without resorting to blending. As mentioned previously, this is due to the fact that the lower the percentage of paraffin-type molecules in the original crude, the lower the boiling points of the various fractions.

The term "asphaltic base" is not generally used because it has no definite meaning. For example, small percentages of asphalt may be extracted from stocks that are predominantly paraffinic in molecular structure. However, it is generally true that the more asphalt in a crude, the lower the percentage of paraffin-type molecules; hence the higher the percentage of naphthenic or low-boiling-point molecules.

The following comparison gives a general idea of the difference between a mineral oil that is definitely paraffinic in structure and a mineral oil that is definitely naphthenic in structure. The test figures are explained in Chapter 14, "Specifications."

		Gravity	*Approx. S.A.E.*	*Saybolt Viscosity at*		*Flash*	*Viscosity*
Type	*Source*	*A.P.I.*	*No.*	*100° F*	*210° F*	*Point*	*Index*
Paraffinic	Pennsylvania	29	30	310	54	450° F	100
Naphthenic	California	20	30	580	56	390° F	20

NOTE: Gravity A.P.I. is a method devised by the American Petroleum Institute. For petroleum distillates it is a more simple method to work with than specific gravity. All the above tests are described in Chapter 14 entitled "Specifications."

Neutral Classification

Another trade term applied to mineral oils is that of "neutral." This classification is somewhat vague but generally applies to light oils. For example, the term "Mid-Continent neutral" or "Pennsylvania neutral" is commonly used to denote a light refined distillate oil having a Saybolt viscosity reading below 300 seconds at 100° F. The term "150 neutral" would indicate that the oil was a light refined oil having a Saybolt viscosity reading of 150 seconds at 100° F. The term "150 Pennsylvania neutral" would indicate that the oil was a light refined oil having a Saybolt viscosity reading of 150 seconds at 100° F and the source of the crude would be Pennsylvania.

Cylinder Stocks

Cylinder stocks are undistilled heavy oils, generally secured from paraffin-base crudes. After refining, they are used for blending with lighter oils, or they may be used without blending for the lubrication of reduction gears, aircraft-engine cylinders and bearings, steam-engine cylinders, and for a variety of other applications where heavy oils are required.

Bright Stocks

This is a general trade name applied to heavy undistilled oils (cylinder stocks) that have been filtered through special clay materials such as fuller's earth. This process lightens the color, removes some of the carbon-forming material, and improves the ability of the heavier oils to separate from water. Bright stocks are classified by color, and, as a general rule, the lighter the color the greater the degree of filtration, all other conditions being the same, as for example, source of crude.

4

Refining Light Distillates and Lubricating Oils

Straight-Run Gasoline and Naphthas

Gasoline and naphthas secured in the original distillation process are known as straight-run products and contain objectionable sulfur and other compounds, many of which have to be removed. These compounds are chemically eliminated by several methods, such as a weak sulfuric acid treatment, followed by washing with water and caustic soda to eliminate and neutralize the acid. As a finishing process, sodium plumbite is used to sweeten the gasoline or naphtha and to take out the most objectionable sulfur compounds, known as mercaptans, which have a disagreeable odor. These procedures vary, according to the particular stock.

Cracked Gasoline and Naphthas

After redistilling cracked gas oil to secure gasoline and naphtha cuts, the refining process is much the same as for straight-run gasoline.

Kerosene

The methods used to refine kerosene are similar to those used for gasoline. Sulfur dioxide is more generally employed to wash out the unsaturated compounds. This treatment is known as solvent refining. The sulfur dioxide removes the unwanted materials by a washing action, as distinguished from a chemical reaction. Sulfur dioxide has a highly selective action in removing the unsaturated hydrocarbons and unwanted materials. Hence for many crudes this refining agent is better adapted to purifying kerosene and producing a clean burning product, free from soot and carbon-forming materials.

Domestic and Burner Fuels

Many light-bodied straight-run fuel oils may be sold direct without requiring much if any refining. Others, particularly fuel oils redistilled from the cracking process, are treated with caustic soda to remove organic acids, phenols, etc. When organic acids are present the reaction with caustic soda produces soapy materials which are removed by filtering through clay. Treatment of light fuel oils varies according to the type of undesirable materials in the fuel oil, but in all cases the refining agent simply eliminates the unwanted materials which would otherwise cause the precipitation of sludge in fuel tanks or interfere with the burning properties.

Refining of Lubricating Oils

In all refining operations carried out on distilled petroleum products the purpose is to remove unwanted materials, and in solvent refining this is accomplished by methods which are very similar to washing a suit of dirty overalls in a tub containing dry cleaning solvent or gasoline. The cleaning agent may be sulfur dioxide, propane, carbolic acid, furfural, etc., but the desired result is the same—to clean the oil by removing unwanted materials, principally unsaturated sulfur compounds, naphthenic acids, etc., depending upon the original source of the crude.

Sulfuric Acid Refining

At one time sulfuric acid was used exclusively for refining lubricating oils, but with the discovery of more selective and more gentle cleaning agents this method has largely been displaced in recent years. The action of sulfuric acid is comparatively severe and produces a chemical combination with unsaturated hydrocarbons rather than a washing-out action. However, there are paraffin-type crudes which react very favorably with this treatment, and the method is still used.

The refined oil is then washed with water and treated with caustic soda or similar alkali material to neutralize the acid. After several washings with water to remove all traces of acid, the oil is ready for dewaxing, or it may be sold direct in the commercial market if dewaxing is not necessary. The acid sludge which is drawn off the bottom of the tank is treated to reclaim as much acid as possible, while the residue or sludge may be treated and reclaimed for such technical uses as emulsifier base for soluble oils. The emulsifier base is extensively used in soluble oils and has a large market.

Sulfur Dioxide Refining

Sulfur dioxide (SO_2) is a gas under ordinary atmospheric conditions, but under pressure, or at a temperature below 32° F becomes a heavy liquid. In liquid form this cleaning agent has a highly selective ability to remove unstable hydrocarbons of the aromatic type and, particularly, unsaturated hydrocarbons. Sulfur dioxide removes the unwanted materials but does not chemically react with them as does sulfuric acid.

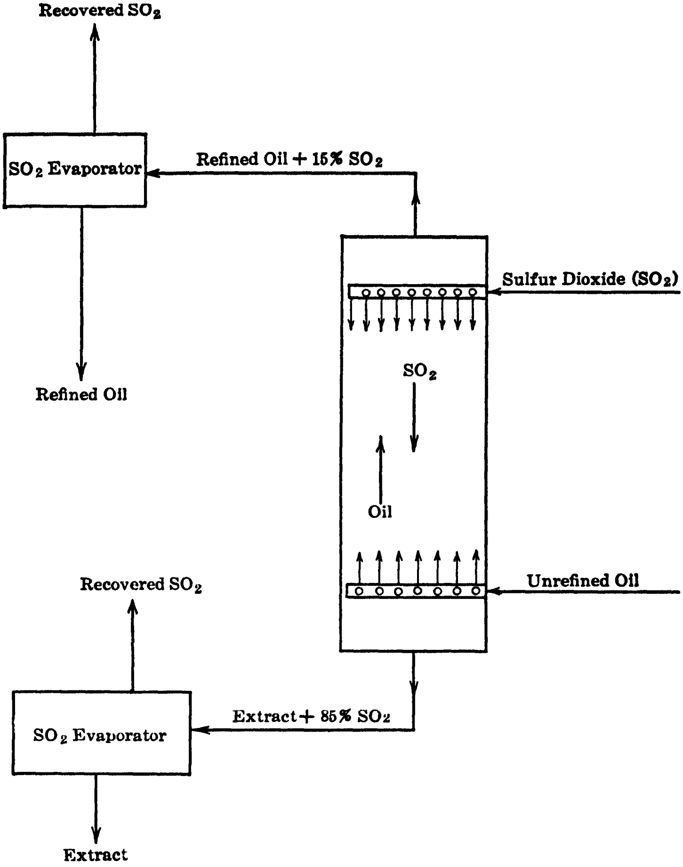


FIG. 1. Diagram of sulfur dioxide refining.

Sulfur dioxide has no effect on the stable paraffin, naphthene, or desirable hydrocarbons of the saturated class, and its cleaning action is mechanical rather than chemical.

This refining method is also economical for the reason that sulfur dioxide can be recovered easily by allowing it to expand into the gaseous form, thereby causing the unstable hydrocarbons extracted from the oil to drop out. Afterwards the gas is compressed, cooled, and returned to liquid form ready for reuse.

In the refining process (Fig. 1) liquid sulfur dioxide is sprayed downward from the top of a tower, while unrefined oil is pumped in at the bottom. Since sulfur dioxide has a much higher specific gravity than any lubricating oil, the heavy sulfur dioxide flows downward, while the lubricating oil is displaced and forced upward, at the same time mingling thoroughly with the cleaning agent, which takes out and carries with it the clinging and unwanted materials from the oil. These materials are unsaturated hydrocarbons and undesirable compounds. This action might be likened to passing a fine-tooth comb through the oil, the sulfur dioxide being a molecular comb.

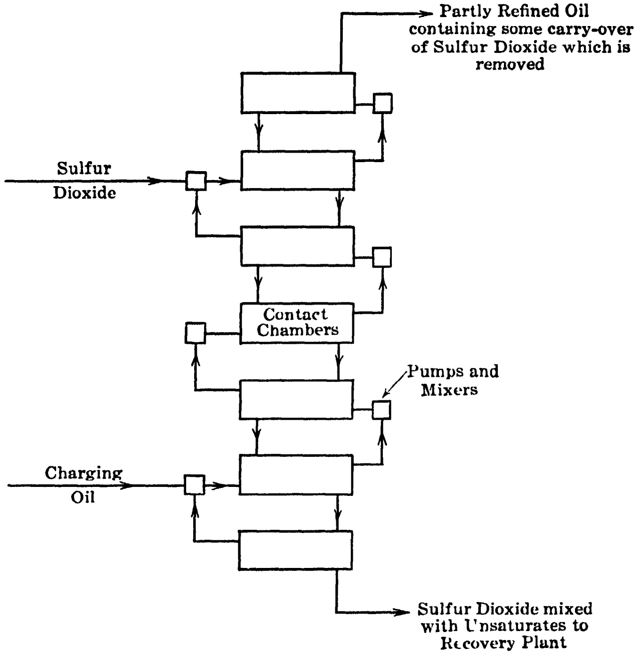

Partly Refined Oil containing some carry-over of Sulfur Dioxide which is removed
Sulfur Dioxide
Contact Chambers
Pumps and Mixers
Charging Oil
Sulfur Dioxide mixed with Unsaturates to Recovery Plant

Fig. 2. Principle of sulfur dioxide refining by stages. Arrows pointing downward indicate flow of sulfur dioxide, which is heavier in body than the unrefined oil and therefore displaces it.

In the majority of oil-refining installations employing this material as a purifying agent the washing cycle is carried out in a series of small mixing chambers arranged progressively to make the cleaning process more selective (Fig. 2). This procedure might be likened to rinsing out a suit of dirty overalls in a series of tubs containing a petroleum solvent, each tub having cleaner liquid than the one before it, until the overalls reach the last tub, where the solvent is clean and the overalls are free from dirt.

Many lubricating oils refined by the sulfur dioxide method are given final treatment with a weak solution of sulfuric acid for the reason that certain crudes cannot be washed entirely clean with the milder agents. For example, many California crudes containing lubricating oil stocks require the acid-finishing treatment to produce an entirely satisfactory lubricating oil that is suitable for use in gasoline, Diesel, and other engines.

Furfural Refining

Furfural is a colorless heavy liquid and, like grain alcohol, is derived by distillation from oats, bran, sugar, etc. After reacting with sulfuric acid, the resulting liquid set free is furfural.

The chemical formula is C_5H_4O, the boiling point is 323° F, and the freezing point is $-34°$ F. With furfural as a purifying agent the purifying or refining process is carried out in a manner that is very similar in principle to the sulfur dioxide process. As with all other solvent refining agents, the furfural process may be used on many types of crude.

Duosolvent Refining

The choice of a particular solvent for refining purposes depends upon many technical factors, principally the type of crude, and in some cases two or more solvents are used to purify lubricating oils.

One example of this method is used on oils containing unsaturated hydrocarbons, asphalt, and wax, and employs cresylic acid or phenol (a product similar to carbolic acid) and the petroleum solvent propane. Owing to the low boiling point of propane, the deasphalting process takes place under pressure in order to keep the propane in liquid form. In this particular method, outlined in Fig. 3, the oil is mixed with a large volume of liquid propane; and since asphalt is not soluble in propane it drops out of the oil-propane mixture and settles to the bottom of the mixing chamber. The oil and propane solution is next pumped into another chamber where the pressure is released, allowing some of the propane to expand into the gaseous form. This rapid expansion of liquid propane into a gas produces refrigeration, thus forming wax crystals in the oil. At this stage the temperature is automatically brought down to about 40° F or below and the wax crystals are removed by cloth filters. After passing through the wax extractors the solution of oil and propane enters a final still where the propane is easily driven out of the oil by distillation and the deasphalted, dewaxed oil is drawn off at the bottom of the still.

In order to avoid the complications of structural design, only the propane section of the process has been described thus far. However, in the other stage of this particular process, cresylic acid mingles intimately with the deasphalted oil and combs out the unsaturated hydrocarbons by means of a counterflow which is arranged in a similar manner to the sulfur dioxide method. The oil travels one way and is displaced by the cresylic acid, which is much heavier and travels in the opposite direction, thereby scrubbing out unsaturated hydrocarbons in the oil. (See Figs. 1 and 3.) The action of cresylic acid is the same as the action of sulfur dioxide, furfural, or other solvent refining agents.

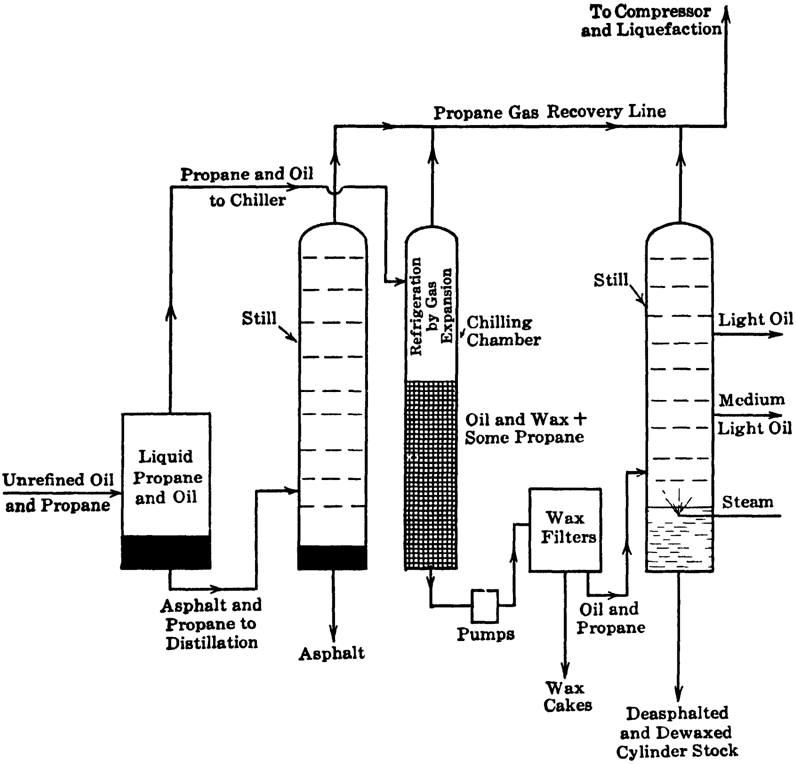

To Compressor and Liquefaction
Propane Gas Recovery Line
Propane and Oil to Chiller
Still
Refrigeration by Gas Expansion
Chilling Chamber
Still
Light Oil
Medium Light Oil
Oil and Wax + Some Propane
Liquid Propane and Oil
Unrefined Oil and Propane
Steam
Wax Filters
Asphalt and Propane to Distillation
Asphalt
Pumps
Oil and Propane
Wax Cakes
Deasphalted and Dewaxed Cylinder Stock

FIG. 3. Diagrammatic sketch showing principles employed in removal of asphalt and wax from lubricating oil by means of propane.

In all refining methods the plant consists mostly of equipment for recovering the solvents. Various claims and advantages are of course made for the different methods, but all are similar in principle. The great advantage of solvent refining lies in the improvement that has come about in purifying oils that were once considered inferior. By means of solvent refining, many oil-bearing crudes which were once thought to be of low grade now form the source of supply for a major portion of our high-grade lubricating oils.

Other Solvents Employed in Refining

Only a few of the solvents employed in refining lubricating oils have been mentioned, but there are many others. The following are also used, some extensively: acetone, benzaldehyde, benzal acetate, cresol, crotonaldehyde, methyl salicylate, nitrobenzene, phenol, and aluminum chloride.

The action of these solvents is the same in principle as those described previously. Preference for a particular refining agent is based on a number of technical factors, principally the source of the crudes.

Overrefining

Lubricating oils may be overrefined by treating them with drastic methods. The result of such treatment is a loss of their lubricating properties. This is exemplified in white medicinal oils which lose practically all lubricating value as a result of the treatment that removes taste, odor, and color.

Additives

Oils are frequently overrefined so as to remove the complex hydrocarbons that interfere with inhibitors that may be added. These will be discussed in Chapter 9.

Clay Filtration

When it is desired to improve the ability of lubricating oils to separate quickly from water, they receive a filtering treatment with clay in the final refining process. This treatment also lightens the color and removes some of the carbon-forming materials. Clay filtration is carried out in two ways, depending upon the degree of refinement required.

The most common and least expensive method is known as "contact" filtration, wherein about 10 to 20 pounds of fuller's earth is intimately mixed with every 50 gallons of hot oil and then filtered out. Separation is accomplished by pumping the oil through a filter press which contains a series of filter cloths, backed up by heavy canvas, wire mesh, and perforated plates. In this way the used clay is removed from the oil on the cloth filters and is recovered in the form of cakes.

The used clay may be reclaimed by burning the impurities adhering to the fine particles, but the clay cannot be recovered indefinitely. As a general rule it is not reclaimed more than 10 to 20 times.

The second method is the "percolation" process, wherein the warm oil passes down through a tower containing fuller's earth. This method is used on turbine oils which must be able to separate quickly from water. The percolation method is also used on transformer oils and similar products where a higher degree of refinement is required.

When the percolation method is employed for filtering heavy oils, they are diluted with a solvent, such as gasoline, to facilitate the flow. After filtration, the solvent is driven off by heat and of course is recovered. Filtered oils of heavy body are generally known by the trade name of "bright stocks." The experienced oil man determines the degree of filtration from a color test, at the same time taking into consideration the source of the crude, viscosity, carbon residue, etc.

The actual reason for the highly effective purifying action of fuller's earth is not known in detail. However, each tiny particle is interwoven with microscopic canals, which remove impurities, such as various undesirable types of hydrocarbons, acidic compounds, and alkalies. The trapped materials are not absorbed by the clay in the same manner as a sponge absorbs water; the materials adhere to the outside areas. Hence, the filtering process is carried out by *adsorption*. Many authorities believe that the filtering process is motivated by a combination of chemical and catalytic action on the part of the clay, but this detail is not actually understood.

Fractionating with Solvents

Heavy lubricating oil stocks may be separated into heavier and lighter fractions with the aid of solvents. For example, paraffin-base stocks have high-range boiling points; consequently fractionating with solvents is receiving particular attention for this type of lubricating oil. The action of various solvents on lubricating oil stocks is rather complicated, because very little is known about the complex molecular construction of lubricating oils. Hence this method is invariably based on preliminary trial and error tests in the laboratory with a particular type of stock as, for example, Pennsylvania and Mid-Continent cylinder stocks.

Solvent fractionation is based on the fact that a solvent such as propane will dissolve a lubricating oil into fractions or cuts, depending upon the temperature of the mixture. For example, propane will dissolve less and less oil as the temperature is raised, the most viscous fractions of the oil being the first to drop out of the solution. Consequently, various cuts may be dissolved out and withdrawn. Afterward, the liquid propane, which has a low boiling point, is allowed to expand into the gaseous form and is then recovered and returned to the liquid form by compressing and cooling it.

The table is an example of three cuts secured by fractionating a filtered Pennsylvania cylinder stock with propane. Notice that the first and second cuts are heavier than the original, while the third is lighter. These results could not be secured by commercial distillation on account of the destructive temperatures required to separate the fractions or cuts.

Cut Number	*Gravity A.P.I.*	*Flash Point, °F*	*Saybolt Viscosity at 100° F*	*Saybolt Viscosity at 210° F*	*Viscosity Index*	*Conradson Carbon*	*Per Cent of Charge*
Original	26.5	550	2340	151	100	1.8	100
1	25.5	575	4030	219	103	2.8	15
2	25.5	560	3500	198	102	2.5	25
3	26.5	540	1500	113	98	1.5	60

Natural Sulfur Compounds in Mineral Oils

All refined mineral lubricating oils contain small amounts of natural sulfur compounds which remain dormant and unreactive for all practical purposes. These sulfur compounds are chemically combined, and most of them are complex and difficult to remove without resorting to drastic chemical treatments, which would remove other valuable constituents from the oil. The percentages and types of sulfur compounds which may be present depend upon the source of the crude and may range from 0.2 to 4.0 per cent.

Even if it were possible to remove completely these natural sulfur compounds, the benefit would be very doubtful, because they are believed to contain preservative qualities which aid in retarding the natural process of oxidation. For example, an average S.A.E. 20 motor, or light turbine oil, may contain 0.5 per cent of various sulfur compounds produced by the original process of nature, and an average S.A.E. 50 paraffin-base aircraft-engine oil may contain about the same quantity or more.

The addition of an artificial compound is often employed to replace and improve upon the natural sulfur inhibitors originally placed in the oil by nature. For this purpose, manufactured sulfur compounds are among the many types added to lubricating oils which must withstand the breaking-down action caused by oxidation. As stated previously, lubricating oils frequently contain an artificial compound to impart resistance to oxidation.

Redistillation of Black Mineral Oils

The finishing treatment of some lubricating oils may involve a redistillation process. For example, oils distilled from asphaltic-bearing crudes may be contaminated by asphaltic materials carried over during distilling. Also, the naphthenic acid content may be high. This acid is sometimes removed by washing with a dilute caustic soda solution. Usually troublesome emulsions are formed. An alternative method is to mix the oil with concentrated caustic soda or with milk of lime and then, without separating the soapy materials formed, to redistill the oil and leave the resulting sludge as a residue.

Sodium Sulfonates

These are obtained as byproducts from the manufacture of white oils which are treated with fuming sulfuric acid. The sulfonic acid sludges are neutralized with soda, and thus converted into sodium sulfonate.

These sodium sulfonates are of two types: oil soluble and water soluble. The oil-soluble types are used as reagents for splitting fatty oils into two components: glycerine and a fatty acid. They are also excellent emulsifying agents, and are used extensively with mineral oils to make them emulsify with water for metal-cutting purposes. The water-soluble sulfonates are used in the textile industry because of their valuable wetting properties.

5

Dewaxing and the Effect of Wax in Lubricating Oils

Lubricating oils contain a certain amount of wax which remains in solution until the temperature is lowered to a point where the wax crystals form an interlocking fibrous mesh which honeycombs the oil with minute cells and thereby prevents it from flowing easily.

The wax content in lubricating oils has a direct influence on the temperature at which the oil will cease to pour. Hence, if a wax-bearing oil is to be used at low temperatures, as, for example, in the crankcases of automotive engines and gear transmissions during cold weather, the wax content must be reduced, to lower the pour point. This is done by chilling the oil to a temperature lower than the desired pour point. The solidified wax formed at this temperature is removed by cloth filters.

There are several types of petroleum wax, but the two of most interest are the paraffin crystalline waxes found in lubricating oil distillates, and petrolatum or amorphous wax found in the more viscous cylinder stocks. The term "amorphous" is derived from the Greek, and means "formless." Vaseline is composed of refined amorphous wax.

The total amount of wax in different crudes may range from 30 per cent to less than 1 per cent. As a general rule paraffin-type crudes contain the highest percentages of wax, while asphalt-bearing crudes run low in wax.

Pennsylvania and Mid-Continent crudes contain a relatively high percentage of paraffin wax. This wax, which remains in the oil after completion of the distillation process, has to be removed to a definite point depending upon the commercial service of the oil. For example, if the oil is to be used for steam-cylinder lubrication the pour point will be unimportant and dewaxing unnecessary. However, if the same oil is to be used in automotive gear transmissions, the wax content must be reduced to a point where the oil will not channel at temperatures prevailing during cold weather, or a synthetic material must be added to break up the honeycomb structure. These materials are known as "pour point depressors." In refinery practice, the oil may be chilled to any temperature by means of ordinary refrigerating machinery, and 0°, −20°, and −40° F are common dewaxing temperatures.

When distillates are rich in wax the freezing process has to be carried out in stages to prevent the formation of a waxy mush too thick for easy filtration. For example, after one chilling cycle, the wax is filtered out; then the clear oil is again chilled and dewaxed at a lower temperature, until the desired pour point is reached.

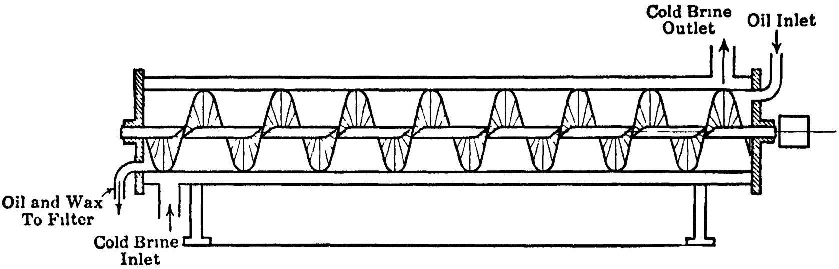


FIG. 1. Line diagram of chiller for removing wax.

In viscous cylinder stocks the oil is cut with a solvent, such as gasoline, and later the solvent is distilled off by the application of heat.

There are several types of chillers and several methods of filtration, but in each the principle is the same. Figure 1 shows a simple chiller employing cold circulating brine which comes from an ordinary ammonia refrigerating plant. The cold brine is pumped around the outside of the chiller while the oil and wax are forced through the barrel by means of a revolving screw.

From the chiller the now viscous oil is pumped under pressure through a filter press which consists of a row of cloth covers backed up by perforated metal plates to prevent rupture of the cloth. When the frames are filled with wax they are withdrawn and the wax cakes fall off. Figure 2 shows a frame design within a wax filter press.

Paraffin wax is of course processed further to eliminate all traces of oil, then treated with sulfuric acid and filtered through fuller's earth to make it white. The particular refining process depends upon the commercial requirement. The refined grades are used for waterproofing, candle making, and a great variety of industrial applications.

In Pennsylvania crudes, two types of wax are generally present: paraffin wax, which is used for a variety of commercial purposes such as waterproofing and candle making, etc., and petrolatum, an amorphous wax, which is a soft wax somewhat like grease in appearance and is the base for products such as Vaseline.

Paraffin wax is not a simple compound of constant melting point but a complex mixture of components which have a melting range between 113° and 149° F (45° to 65° C).

In recent years considerable research has been carried out to find new solvents that may be mixed with viscous oils to facilitate dewaxing. Gasoline is used as a solvent, but mixtures of benzol and acetone are finding popularity on account of their superior ability to assist in throwing out wax. Another combination is a mixture of methyl-ethyl-ketone, toluol, and benzol. Mixing the oil with liquid propane and allowing the propane to expand into the gaseous form is another method of producing refrigeration and allowing the wax to be filtered out. This method forms a part of the duosolvent refining process which was described previously.

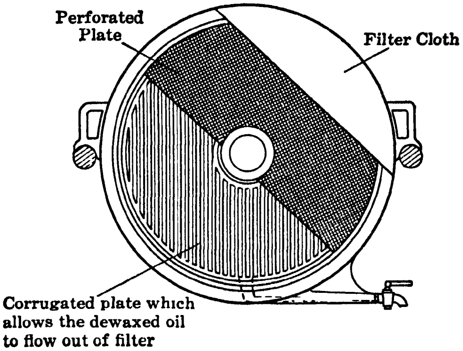

Perforated Plate
Filter Cloth
Corrugated plate which allows the dewaxed oil to flow out of filter

FIG. 2. Cut-away section of filter press plate for removing wax.

Effect of Wax at High and Low Temperatures

The pour point of an oil is an extremely important consideration for low-temperature operating conditions. However, the ability of an oil to pump easily at low temperatures is also an important consideration. In this connection paraffin-base oils pump more readily than naphthenic-base oils at low temperatures because they exhibit less change in viscosity with change in temperature. However, pour point is a factor when the oil must flow into the pump suction.

Wax has a viscosity index of 160–200 (see Chapter 10), so that wax-bearing oils exhibit less change in viscosity as temperature changes.

Wax is not affected by distillation and, during this process, passes over with the various fractions of the oil. Wax is soluble to some extent in the various lubricating fractions. As the wax has a flash and fire point equal to the heaviest oils, it appears to have little effect when oils are used at high temperatures.

Pour Point Depressors

In order to remove wax for the purpose of lowering the pour point of a waxy oil, the procedure followed is generally a compromise, wherein part of the wax content is removed by refrigeration and a synthetic material is added to further lower the pour point to the desired service temperature. At low temperatures, wax crystals form a honeycombed structure throughout the oil which retards flow. Hence the purpose of an additive is to break up this structure. Obviously this procedure reduces the cost of removing a considerable percentage of wax by means of refrigeration. The subject of pour point depressors will be more fully developed in Chapter 9.

6

Fatty Oils

Fatty oils are obtained from animals, the seeds of vegetables, and fish. They are sometimes used alone but are frequently compounded with mineral oils.

Animal, vegetable, and fish oils are sometimes referred to as "fixed oils" because they cannot ordinarily be distilled without decomposition. However, the more common designation is "fatty oil." Animal oils employed for compounding with mineral oils are secured by boiling down animal carcasses; vegetable oils are secured by pressing the seeds of plants or by extracting the oil with solvents; and fish oils are obtained by boiling down the blubber of fish. Like mineral oils, these three types are composed mostly of hydrogen and carbon, differing only by the addition of oxygen.

Virgin fatty materials are split into their respective fractions of solids, oils, glycerine, oleic acid, etc., by means of steam heat and other methods, which form another study in refinery processes, as, for example, the extraction of oil from crushed seeds and nuts by solvents. However, in this text we are interested only in the use of these materials after they have been refined and made ready for the commercial market.

When exposed to air, many vegetable oils rapidly absorb oxygen and form thin elastic films. This type cannot be used for compounding with mineral lubricating oils. They are termed "drying oils," of which the best known is linseed oil, largely used in paints. A few of the less rapid or nondrying oils, such as rapeseed, are employed for compounding with mineral oils.

At elevated temperatures all fatty oils absorb oxygen rapidly and become drying oils. For this reason it is desirable to compound the minimum of a fatty oil with a mineral oil.

It will be noted in Table 1 that some of the principal fatty acids are complex. For simplicity these acids are frequently referred to as

TABLE 1. FATTY ACID COMPOSITION OF FATS AND OILS *

These figures are approximations only, based on many experimental determinations reported in the literature. Individual samples of the fats and oils may vary from the figures shown.

	Saturated Acids								*Unsaturated Acids*			
Fat or Oil	Caproic (C_6)	Caprylic (C_8)	Capric (C_{10})	Lauric (C_{12})	Myristic (C_{41})	Palmitic (C_{16})	Stearic (C_{18})	Arachidic (C_{20})	Oleic (C_{18}-2H)	Linolic (C_{18}-4H)	Linolenic (C_{18}-6H)	Miscellaneous
Babassu oil		6	3	46	20	7			18			
Butter	2	1	2	4	10	28	10	1	35	4		3[1]
Castor oil							1		4	5		90[2]
Coconut oil	1	9	8	45	20	8	3		5	1		
Cod liver oil					4	10	1					85[3]
Corn oil						7	4		46	43		
Cottonseed oil					1	21	2		30	46		
Lard					1	28	13		48	6		4[4]
Linseed oil						4	5		7	49	35	
Menhaden oil					6	16	1			30		47[5]
Oiticica oil						7	5		5	6		77[6]
Olive oil						11	2		80	7		
Palm oil					1	40	5		46	8		
Palm kernel oil	1	3	5	50	15	8	2		15	1		
Peanut oil						8	3	3	61	22		3[7]
Perilla oil						7			8	38	47	
Sesame oil						8	4	2	46	40		
Soybean oil						8	5		28	56	3	
Tallow					3	28	22		45	2		
Tung oil						4	1		10	2		83[8]
Whale oil					6	13	1		25	20		35[9]

* *Chem. & Met. Eng.*, December, 1940.

[1] 3% butyric (C_4).

[2] 90% ricinoleic (12-hydroxy-oleic).

[3] 14% C_{16}-2H; 28% C_{18}-3H; C_{20}-5.5H; 15% C_{22}-7H.

[4] 2% C_{16}-?H; 2% C_{20} and C_{22}-?H.

[5] 16% C_{16}-?H; 19% C_{20}-10H; 12% clupanodonic (C_{22}-10H).

[6] 77% licanic (4-keto-elaeostearic).

[7] 3% behenic (C_{22}).

[8] 83% elaeostearic (C_{18}-6H).

[9] 17% palmitolic (C_{16}-4H); 18% clupanodonic (C_{22}-10H).

oleic acids. The fatty acid in an oil is expressed as an equivalent amount of oleic acid, although oils vary in their molecular structure.

All refined fatty oils contain a small amount of natural fatty acid, and when exposed to the air the amount increases until the oil becomes rancid. Hence, the fatty oils employed for compounding with mineral oils are invariably well refined, deodorized products, from which impurities have been extracted to reduce their oxidizing tendencies. The acidity of a compounded oil is raised on account of the fatty acid introduced by the fatty oil. In a similar manner, the great majority of mineral oils contain a small amount of natural "petroleum acid." These fatty acids belong to a group of organic compounds and must not be confused with inorganic acids, such as sulfuric and hydrochloric acid.

The addition of a fatty oil to a mineral oil increases the adsorbed film on the surface, which raises the load-carrying ability of oil films, a property that is advantageous in special applications.

In the presence of heat, mineral oils act differently from fatty oils. A simple experiment will show that fatty oils will move toward the hottest part of a flat iron plate, while mineral oils tend to "shy" away from heat. This feature is due to a more rapid lowering of surface tension within the fatty oil, which improves the penetrating and spreading property.

Mineral oils on a metal surface heated to about 450° F tend to form small spheres, like water on a greasy frying pan, when the holding force within the molecules becomes greater than the affinity of the surface molecules for the metal. This ability to wet the metal surface in an unbroken film is a necessary function of lubrication. For example, reciprocating steam engines operating on high-temperature steam (about 600° F) are difficult to lubricate, and present aircraft engines with cylinder wall temperatures slightly over 400° F are now near the upper limit at which straight mineral oils will wet the metal.

The solidifying point for the majority of refined fatty oils (animal, fish, and vegetable) is below the freezing point of water. A general average range is about 25° to 10° F. This property is very convenient where the compounded oil is used in cold climates. However, compounded oils should not be stored in cold locations or left outside during cold weather. In the event that separation takes place because of low temperature, the drum should be left in a warm location for a day or two, then rolled back and forth on the floor to agitate the compound into suspension again.

Fatty oils have relatively high flash points, and few are below 350° F. For example, tallow, lard, and castor oil have flash points of about 550° F or above, which is comparable to high-grade mineral oils of cylinder stock. In fact, medium-viscosity steam cylinder oils of Pennsylvania origin also have flash points of about 500 to 550° F.

Hundreds of variations are possible in the art of compounding various materials with mineral oils. However, the most common applications have been outlined under the headings which follow. The basic principle of compounding is to add oily materials that will improve the load-carrying ability of the finished oil under certain conditions, or impart particular qualities which straight mineral oils do not possess.

All vegetable, animal, and fish oils will support bacteria. Care should be taken to see that the oils are sterile.

Tallow Oil

This material is obtained from cattle, sheep, and goats by melting the fat with live steam in large kettles. At temperatures between 60° and 80° F, tallow is a mixture of solid and fluid fats, but, when subjected to pressure, the tallow oil may be separated from the solid tallow without difficulty.

The type of tallow oil employed for compounding with mineral oils is a highly refined grade, with a clean sweet odor, almost white in appearance. Owing to the fact that the fatty acid content is very low, the general trade name for this grade is "acidless tallow oil." The specific gravity ranges from 0.911 to 0.915, the flash point by the open-cup method is about 550° F, the pour point about 40° F, and the Saybolt viscosity about 200 seconds at 100° F.

Tallow oil is a popular constituent of steam cylinder oils where it produces a tenacious emulsion in the presence of moisture. In gear lubricants, tallow oil imparts additional load-carrying properties to oil films. As a general rule, the maximum quantity of tallow which a mineral oil will hold in suspension is about 12 per cent.

Lard Oil

Lard oil is obtained from hog fats, and the general properties are similar to those of tallow oil. The best grades are commonly employed in steam cylinder oils to produce a tenacious emulsion in the presence of moisture. Other uses are as a cutting oil for machine tool work and as a constituent in mineral oils employed for lubricating textile machinery. In the latter application, oil stains on fabrics may be washed out more readily when the mineral oil is compounded with 15 to 25 per cent of lard oil by weight.

The specific gravity of lard oil is about 0.915, flash test by the open-cup method about 550° F, pour point about 35° F, and Saybolt viscosity 100 to 200 seconds at 100° F.

Lard oil is also used extensively as a carrier for sulfur in extreme-pressure lubricants and metal-cutting oils. This process is carried out in steam-heated kettles where lard oil may be processed to absorb about 14 per cent of sulfur by weight in the "cooking" process. The reaction causes a considerable rise in viscosity, and the finished base oil may have a Saybolt viscosity of about 350 seconds at 210° F. The sulfur-lard oil base is then added to mineral oils in any desired proportion.

Among its other uses, lard oil is sometimes compounded with mineral oils employed for tempering steel and steel alloys. The purpose in this application is to reduce the effect of "vapor bubbles," which tend to form on the hot steel surfaces and impair uniform tempering. Owing to the fact that animal, vegetable, and fish oils have lower surface tension characteristics than mineral oils, they tend to flow and creep more readily on the surface of hot metal and thereby release vapor bubbles. Winter-strained lard oil is the designation of purified lard oil. It is obtained by refrigerating the oil and filtering.

Rapeseed Oil

Rapeseed oil is obtained from plant seeds and has a pale, clear yellow color. The specific gravity is about 0.915, and the pour point is about 15° F. Before this oil is compounded with mineral oil, it is generally subjected to blowing with air, which oxidizes, stabilizes, and reduces the drying tendencies of the finished product. Rapeseed oil is a popular constituent of marine engine oils which generally contain from 10 to 20 per cent of "blown rape." The blowing of rapeseed with air may increase its viscosity from 250 Saybolt seconds at 100° F to about 1000 Saybolt seconds at 210° F. When compounded with mineral oils the viscosity is influenced pro rata. As a general rule, rapeseed is employed for compounding where water tends to creep into machine bearings. Emulsifying with the water, it tends to prevent the displacement of the oil film from the metal, thus furnishing lubrication and preventing rusting.

Castor Oil

Castor oil is obtained from the seeds or beans of the Ricinus plant. The finished product is very viscous, and its use for blending with mineral oils is not extensive. The specific gravity is about 0.965, pour point below 0° F, and Saybolt viscosity about 1400 seconds at 100° F. Castor oil is occasionally employed for compounding with heavy mineral oils which are to be used for lubricating reduction gears, as, for example, bath-oiled worm gears. However, the products of oxidation with castor oil are tough, stringy, and gummy, particularly if high temperatures are a factor.

As a lubricant for internal-combustion engines, castor oil has a viscosity rating of an S.A.E. 50 motor oil and a high viscosity index rating. It is seldom used, as it produces hard varnish and tough stringy deposits in the crankcase. It can only be used for a very short period of time, before the engine must be completely dismantled for cleaning. Castor oil is often compounded with sulfur and mineral oil to provide cutting oils and extreme-pressure oils. Since castor oil does not readily mix with mineral oils, lard or some other fatty oil is added to aid in providing a homogeneous mixture.

Sperm Oil

Sperm oil is obtained from the blubber and head of the sperm whale. Depending upon the size of the whale, the yield per whale ranges between 1000 and 3000 gallons of oil.

The specific gravity is about 0.88 flash point by the open-cup method about 500° F, pour point 20° to 30° F, Saybolt viscosity 70 to 115 seconds at 100° F, and viscosity index 180.

Sperm oil is light, fluid, and pale yellow in color, blends easily with mineral oil, and has excellent properties for absorbing and retaining sulfur. This latter feature is advantageous where compounding with sulfur is desired, as, for example, in metal-cutting oils which are manufactured by the fundamental process of gently cooking sulfur into sperm oil and then adding the finished base to a mineral oil in various proportions. This same method is employed in manufacturing gear oils of the extreme-pressure type where the mineral oil is more viscous. Sperm oil will combine with sulfur in the approximate ratio of 10 parts sulfur to 100 parts sperm oil. This process raises the viscosity to a considerable extent, owing to the oxidizing influence of the heat during the cooking process.

Menhaden, Seal, and Whale Oils

Menhaden oil is obtained from the menhaden, a small fish about the size of a herring. The principal use for this oil is in the leather industry. However, this oil is occasionally employed as a quenching medium for steel parts and tools such as saws and blades. The flash point is about 460° F for an average grade.

Seal oil is obtained from the blubber of seals and after being compounded with sulfur is used for blending with mineral oils to manufacture metal-cutting oils and extreme-pressure gear oils.

Whale oil is obtained by boiling down the blubber of different species of whales, which sometimes yield up to 7000 gallons for a single animal. Whale oil is employed for the same purposes as sperm, seal, and other fish oils but is less expensive. Some commercial grades have rather rapid drying tendencies, which are undesirable in mineral oil compounds. However, "first runnings" obtained from the separated blubber in the boiling-out process are sometimes used for retaining sulfur in cutting and gear oils. Whale oil is occasionally employed for quenching steel, as are most other fish oils. However, the practice of using fish oils for quenching purposes has been almost entirely eliminated because of the over-all superior qualities of mineral oils. The flash point of a good grade is about 500° F, and the pour point 15° to 30° F.

Neat's-Foot Oil

Actual neat's-foot oil is obtained by boiling out the hoofs of cattle, but commercial grades may include the oil from the hoofs of horses, sheep, and hogs. Neat's foot has drying properties and is seldom used for compounding with mineral oils. It is used by the leather industry and in factories for belt dressing. For the latter application neat's foot is sometimes compounded with light mineral oil. Neat's-foot oil tends to form solids even at room temperatures. These solids, so-called foots, may be removed by chilling the oil and filtering.

Rosin Oil

This product is secured by the distillation of colophony obtained from trees (common rosin). Rosin oil has semidrying properties and is therefore not very suitable for compounding with mineral oils, but a small amount is sometimes used in formulas for rust-prevention oils and compounds. Rosin has good adhesion and resistance to shear *properties. These properties may be desirable in some lubricants. Though rosin is also used in some belt dressings, it is detrimental to leather.*

Olive Oil

The principal use for olive oil in the lubricating field is in water-soluble oils of the type used in the textile industry. These soluble oils are mixed with water and sprayed on the wool stock before it enters the combing machines. The purpose is to lubricate the wool fibers during the combing operation. Later, the soluble oil is washed out in vats.

Coconut Oil

Edible coconut oil is also used in the textile industry for compounding with mineral oils to manufacture soluble oils of the type employed to lubricate wool fibers. The soluble oils are made to various formulas, and the oil and water emulsion is applied by means of a spray just before the combing process. Emulsions of oil and water vary in proportion on account of the widely different practices in different mills.

Degras

Degras, commonly called lanolin, is refined from oil that is extracted from raw wool during the washing process. This product is sometimes used in steam cylinder oils to produce an emulsion in the presence of low-temperature wet steam. Degras is also used in tempering and quenching oils and in mold oils for clay brick forms. The flash point of degras is about 450° F.

Elaine

Elaine is a fatty oil obtained from animal fats. Another name is oleic acid. Small amounts are sometimes used in mineral oils employed to lubricate machinery equipped with oil cups and hand-oiling methods. The amount of elaine is generally not more than 1 per cent in this type of lubricating oil. The compound increases the load-carrying capacity of oil films, and, to a small extent, imparts tackiness. Saybolt viscosity is about 100 seconds at 100° F. This material is also effective in preventing rusting when added to mineral oils in amounts of ¼ of 1 per cent, but should not be used in lubricating oils in the presence of lead-alloy bearings because lead oleate may be formed at the expense of the bearings.

Petrolatum

Mineral oils and compounds adapted to rust-prevention purposes are compounded with a variety of materials. A popular compounding formula is petrolatum or amorphous wax, rosin oil, lanolin, and a corrosion inhibitor, such as sodium or potassium bichromate. Petrolatum is also the main constituent of Vaseline.

Palm Oil

Palm oil is obtained from the fruit of the palm tree. Its principal use is in drawing compounds and rolling of tin plate.

Adhesive Compounds

Materials that are effective in reducing drippage from machine bearings lubricated by hand-oiling methods may be added to oils. Latex and several synthetic products are added to oil to impart this clinging property to oils and greases.

Soaps

Mineral oils are sometimes mixed with various types of soap thickening agents to reduce drippage from hand-oiled bearings, open gears, chains, and similar machine parts. These lubricants are sometimes termed "nonfluid oils" or "semifluid greases." They generally contain a calcium, sodium, or aluminum soap, which imparts a characteristic stringy property to the mineral oil. As explained in Chapter 12, entitled "Greases," the great majority of soaps are manufactured from animal fats; and for oil-thickening purposes the types employed are not generally soluble in water. Perhaps the most appropriate name for this type of lubricant would be fluid grease.

Metallic soaps, such as lead soaps, manufactured by combining lead oxide with a fatty acid, such as oleic (lead oleate), are employed in mineral oils which impart high load-carrying properties to oil films. This type of lubricant is classified as mild extreme-pressure lubricants.

Extreme-Pressure Agents

Chlorinated compounds are frequently added to mineral oils. Under these circumstances a thin film of metal chloride is produced when the oil film breaks, and this action prevents scoring or welding.

The amount required to produce this effect is comparatively small, and gear oils generally contain no more than 1 per cent, while metal-cutting oils may contain about 0.5 per cent. Often the oil may contain both sulfur and chlorine in the form of prepared compounds.

Identification of Compounded Oils

An oil compounded with a fatty oil may be identified by the saponification number and iodine number. The percentage of compounding or the particular fatty oil used when unknown requires very complicated test procedures. It is common practice for the compounder of a lubricant to name the fatty oil employed. With this knowledge, it is relatively easy to calculate the percentage of compounding. (See saponification and iodine number, Chapter 10.)

7

Blending

To dispel early some popular misconceptions on mixing mineral oils, it is a fact that all petroleum products will blend with each other regardless of the source of the crudes. Furthermore, they may be mixed in any proportion of light and heavy oil to form an oil that is nonseparating, except by distillation. Gasoline, kerosene, and light fuel oils are blended by simply running the mixtures through centrifugal pumps. Lubricating oils are generally brought together in iron containers equipped with steam coils and the temperature is raised to 135° F. In order to further accelerate the blending action, jets of compressed air bubble up from the bottom of the containers and produce agitation. The process is very simple and merely carried out in this manner to produce rapid blending.

This matter of blending has a direct influence on the quality of the product for the reason that any combination of different-bodied oils may be used. Blending should be approached with full knowledge of the oils being blended and of their intended use. For example, if a motor oil is made from a blend of light spindle oil and very heavy cylinder stock the resulting blend may be an S.A.E. 30 or medium-bodied motor oil, but the effect on the engine will be detrimental. The heavy stock will tend to produce carbon, while the high percentage of light spindle oil will tend to distill off, also leaving behind gummy compounds and carbon residue. Hence, the blend very often influences the quality and, of course, the price per gallon of lubricating oils.

Blending by Viscosity

Lubricating oils may be blended by means of viscosity blending charts, an example of which is shown in Fig. 1, or by prepared blending tables. Either procedure is very simple. Viscosity temperature charts are published by the American Society for Testing Materials. They are adaptable to blending lubricating oils and are supplied with complete instructions.

Assuming that an oil having a Saybolt viscosity of 400 seconds at 100° F is required (S.A.E. 30) and only two oils are available, one having a Saybolt viscosity of 800 seconds at 100° F (S.A.E. 40) and the other a Saybolt viscosity of 200 seconds at 100° F (S.A.E. 10). To secure the desired blend, place a straight edge on the left-hand side at the figure 800 and the other on the right-hand side at 200. Mark the point where the straight edge cuts 400, and directly under this point read off the percentage of light oil. Thus the blend would consist of 47 per cent of the light oil and 53 per cent of the heavy oil.

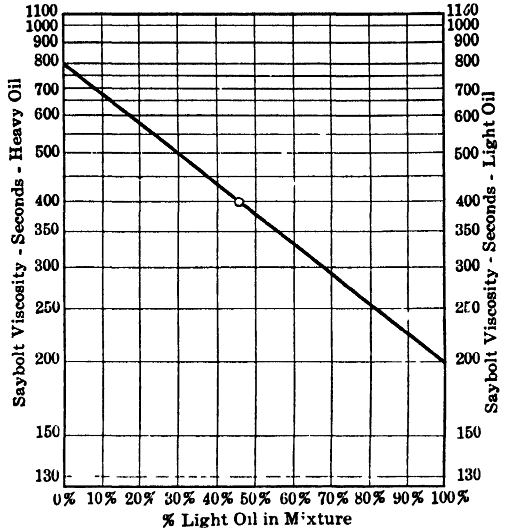


FIG. 1. Saybolt viscosity blending chart for heavy lubricating oils.

When calculating blends of lubricating oils by means of a chart, the viscosity reading of each oil must be taken at the same temperature. For example, if the viscosity of one oil is given at 210° F and the other at 100° F, the chart cannot be used until the viscosities of both oils are given at either 100° F or 210° F.

The chart illustrated in Fig. 1 is for use in blending heavy-bodied oils; for light-bodied oils and petroleum liquids a similar type of chart is available and is used in the same manner.

For more detailed information on the significance and definition of viscosity refer to Chapter 10, "Physical Tests."

8

Solid Lubricants

Solid lubricants are useful in reducing friction where oil films cannot be maintained because of pressures or temperatures. Being dry they are useful for some applications where oils tend to gather dirt and become gummy.

These lubricants may be divided into two general classifications. The first group are mechanical in nature and have no particular affinity for a metal surface in spite of many claims that are made expounding this property. The second classification has a chemical affinity for most metals although no chemical reaction. All solid lubricants range from mild polishing agents to mild lapping agents. Neither class provides adequate protection from rusting, which would indicate that the solid film is not impervious to moisture.

All solid lubricants interpose a layer of material between the moving surfaces. Solid lubricants should be softer than the materials being lubricated. As an example, emery and ferric oxide will reduce friction but rapidly score and abrade the metal surfaces. Solid lubricants are fixed and therefore cannot transmit heat or contaminants from the bearing as can a circulating oil.

Table 1, using rough approximations, illustrates the need for care in considering the use of solid lubricants.

TABLE 1

Lubricant	*Coefficient of Friction*	*Load, psi*	*Speed, sfm*	*Foot-Pounds per Minute*	*Film Temperature Rise, °F*
Oil film	0.003	1000	100	300	5.1
MoS_2	0.03	1000	100	3,000	51.0
Mica	0.30	1000	100	30,000	510.0

1 Btu = 775 ft-lb.

Graphite

Graphite is manufactured from coke or anthracite coal. A great deal of graphite for nonlubricating purposes is mined, but mined graphite contains many impurities which are very difficult if not impossible to remove completely.

Graphite is normally obtained in flake form. The particles are sometimes milled to a very small size, and are called colloidal graphite in this form. This material may be used in the dry form, mixed with various oils, greases, and solvents which act as vehicles to carry the graphite to the moving surfaces.

Talc

Talc is powdered soapstone. The material is generally refined by air flotation, which permits the larger particles and impurities to sink out of the air stream. Like most natural products it contains a small percentage of impurities. A common use is as a mild lapping compound for breaking in machine parts.

Mica

Mica is a mineral found in nature. The mining and refining processes are much the same as for talc. Sheet mica is widely used as a dielectric in electrical equipment. In the finely powdered state it is used for running in bearings, where it functions by lapping out the high spots to increase the bearing area.

Zinc Oxide

This material is a white metallic oxide of zinc. The very small particle size makes it of some interest as a solid lubricant. Because of its favorable color it has applications where darker lubricants are objectionable, as in textile, food, and chemical processes.

Silver Sulfate; Lead Iodide

Silver sulfate, lead iodide, and many other metallic compounds exhibit very low coefficients of friction. At the present time this class of solid lubricants has been experimentally tried but has not found commercial applications.

Molybdenum Disulfide

Within the last few years molybdenum disulfide has found increasing acceptance as a solid lubricant of the chemical type. The molecular structure of an atom of molybdenum coupled to two atoms of sulfur provides a strong bond to metals that are active with sulfur. Some of these are, of course, iron, silver, and copper. Some researchers believe that the low coefficient of friction between molecules is caused by the sulfur-to-sulfur bond, which shears easily. Others prefer to believe that the low shear is the result of adsorbed moisture or other films on the surface of the fine particles of molybdenum sulfide.

In order to obtain the maximum performance, the metal surfaces to be lubricated should be well cleaned before applying a chemically active solid lubricant. It may be used with a solvent to carry the solid lubricant to the moving surfaces. Some applications are in metal-forming, instrument lubrication where lubricants tend to gather dirt, springs, electrical switch gear, etc. Solid lubricants find their principal use in heavily loaded, intermittently operated equipment.

9

Additives for Lubricants

Continuous demand for increased efficiency results in the increased complexity of machines. Lubricant requirements are more exacting as speed, temperature, and continuity of operation increase. These requirements have been successfully met by the petroleum industry. During the years since the mid-1930's entire new classes of lubricants have been developed. These lubricants use petroleum oils and add chemicals, called additives, to give the desired results. Additives have introduced an entire new industry into the lubrication field. The chemistry of additives is complex and beyond the scope of this book, but the lubrication engineer should have a working knowledge of additives and their function so that he can apply them intelligently.

Engineers are now confronted with such designations as "compounded oil," "heavy-duty oil," "inhibited oil," and "detergent oil," with the result that many must wonder where all these terms come from and where a line of distinction can be drawn. Actually, the choice of a descriptive term is often a matter of individual preference, but eventually one term prevails with the public, and that term is finally adopted by popular majority. No matter what term is used to describe a particular lubricating oil, the following descriptions may be found of assistance to those who may sometimes be confused.

Mild Extreme-Pressure Lubricants

The mild extreme-pressure lubricants (mild E.P.) have been developed for some of the applications where conventional lubricants fail to protect the metal surfaces. These are polar in nature and do not change the surface of the metal chemically. The polar compounds orient themselves to the metal surfaces and are extremely difficult to remove. We might liken them to the bristles in a brush, which bend easily but are difficult to pull out. Inasmuch as mild E.P.'s carry higher loads than straight petroleum oils, they are sometimes referred to as oiliness agents.

Lead Soap

Lead soap is produced by treating a fat with lead hydroxide, which results in lead soap and glycerine. Lead soaps do not thicken oils appreciably and therefore are very popular as an additive for fluid oils. This type of oil is represented in the S.A.E. 80 and 90 gear oils. There are two types of lead soaps: lead oleate and lead naphthenate.

Lead Oleate

Lead oleates are generally incorporated into base stocks which are susceptible to oxidation, with a resulting increase in viscosity. They have a tendency to absorb water and to foam in the presence of moisture. They also tend to separate after long storage.

Lead Naphthenate

Metallic lead is saponified by naphthenic acids to a lead soap. These soaps may be blended with oxidation-resistant oils. The resultant lubricant has less tendency to foam and will resist separation during storage.

Oleic Acid

Oleic acid is an organic acid, which, it has been noted (Table 1, Chapter 6), is found in almost all fatty oils. It is used as a mild E.P. by adding up to 1 per cent to a mineral oil. All fatty oils are polar in nature, although they vary widely in their ability to carry loads.

Full Extreme-Pressure Lubricants

Full extreme-pressure lubricants are sometimes referred to as "hypoid lubricants." They have been developed to carry the loads where mild E.P.'s fail. These extreme loads generally occur under a shock condition. Most extreme-pressure lubricants are likely to contain compounds of sulfur, chlorine, or phosphorus. These compounds prevent welding, galling, and scuffing of metal surfaces. Under high loads the high points of the surfaces break through the polar films, and temperatures are sufficiently high that welding occurs. At these temperatures the chemicals in the full E.P.'s become active and react with the surfaces to prevent welding. These coatings—sulfides, chlorides, or phosphides—provide what we might call a dirt film. This "dirt film" functions in much the same manner as copper, which has to be clean in order for solder to stick.

At normal operating temperatures these chemical compounds are inactive and have little if any action on the metal surfaces. Under sustained loading, where E.P.'s are required, a measurable rate of wear is to be expected, as well as fatigue of the parts, from the high repeated stresses. Many gears fail in this situation, and the gear teeth are broken out at the roots.

Antioxidants

Antioxidants are employed in many of the additive oils. Oxidation is the primary action by which an oil changes its characteristics and thus causes difficulties in service. The chemical addition of oxygen to the hydrocarbons forms chemical compounds such as resins and organic acids, some of which may be corrosive, and increases viscosity, all of which may be harmful. The progressive reaction of oxidation can be shown by the simple hydrocarbon methane.

Methane → Methyl alcohol → Aldehyde → Formic acid → Carbonic acid

$$CH_4 \rightarrow CH_3OH \rightarrow HCHO \rightarrow HCHO_2 \rightarrow H_2CO_3$$

Heat accelerates oxidation, as it does all chemical reactions. At temperatures of 60 to 80° F, the rate of oxidation is so low that no significant changes in the oils are noted. A pertinent fact is that the rate of oxidation doubles for approximately each 15° F rise in temperature. This means that a lubricant that would give satisfactory service for 5 years at 120° F would last only $2\frac{1}{2}$ years at 135° F. At 200° F it would last only 6 weeks. It is generally conceded that oxidation is a very important consideration at temperatures above 150° F. A lubricating oil molecule that is oxidized speeds up the oxidation process. It is the function of an antioxidant to prevent the catalytic reactions from taking place. We might liken this whole process to a car coasting downhill without brakes until a disastrous speed is attained. Frequent applications of the brakes may keep the car under control but not necessarily bring it to a halt. Thus do antioxidants control oxidation within tolerable limits, provided the temperatures are not too great.

Detergents

Detergents are added to some lubricating oils to disperse and hold dirt so that the dirt particles cannot agglomerate into large masses which may block oil passages. The property of dispersing finely ground solid materials in a liquid is well known in the field of chemistry, and agents possessing the power to bring about this result are known as "peptizers." Many fine-particle or colloidal suspensions may be prepared by distributing a finely ground solid material in a liquid by the use of a suitable dispersing agent, which prevents the small particles from sticking together or coagulating. In this manner a colloidal suspension of graphite in water may be prepared with the aid of a little tannin. However, the additive agents employed in lubricating oils are known as detergents rather than peptizers because they impart a cleansing action as well as retaining deposits in suspension in a finely divided form.

The metallic soaps are commonly used as detergents. These soaps act in much the same manner as laundry soap in holding dirt in suspension. Metallic soaps accelerate the oxidation of oils by keeping metal surfaces clean; this permits the metals to act as catalysts, besides leaving them in condition for volatile fatty acids, as well as moisture, to corrode. Antioxidants are generally used with this class of lubricants.

There is a limit to the amount and types of contaminants that detergent oils can control. Their principal use has been in internal-combustion engines, where they act upon the various byproducts of dirty fuel. Some industrial applications are being found.

Metal Passivators

Most metals are chemically active with air, oils, and other metals. A material which coats the metal surfaces in such a manner as to retard this activity is called a passivator. Oils in service dissolve metals. This does not mean that the metals are entirely consumed, as only traces are found. Only a few parts per million of metal in oil will cause the oil to deteriorate rapidly. The passivative effect is usually supplied from the additives, such as antioxidants, detergents and E.P.'s.

Corrosion Inhibitors

Corrosion of machine parts generally associated with lubricants under service or storage conditions can be accounted for, as a rule, either as rust due to the atmosphere, or as an oxidation product of the lubricant. Corrosion due to the oxidation of the oil is indicative of the need for additive oils.

Rusting corrosion of metal parts may be materially reduced by the addition of a corrosion inhibitor. The inhibitors, which are generally of a polar nature, attach themselves firmly to the metal surfaces in a thin film. It is most difficult for water to work under and displace these films.

Corrosion inhibitors have improved operation to a large extent, and yet under some conditions of operation further improvements are desirable. Rusting still occurs where large quantities of water are present and above the oil level, where the oil tends to drain off.

Emulsifying Agents

Emulsifying agents are used in lubricating oils to form an emulsion with water so that each particle of water is surrounded by oil. This prevents the water from coming in contact with metal surfaces and causing corrosion. Such materials as rapeseed oil, tallow, sulfinates, and metallic soap are used as emulsifiers.

Antifoam Agents

In most circulating oil systems air is entrained in the oil in large volumes. The use of additive oils, together with the higher rates of circulation, sometimes causes foaming difficulties, owing to the inability of the oil to release the air bubbles quickly enough. The high-polymer silicones appear to be very efficient foam suppressors. As little as 0.003 of 1 per cent by volume is all that is required, but, strangely enough, too much is ineffective. The silicones are not very miscible with mineral oils, so that frequently they are furnished mixed with a light oil for ease of use.

Viscosity Index Improvers

All oils change in viscosity with changes in temperature. In applications where the ambient temperature is likely to vary widely, it may be desirable to have a lubricant that changes least with temperature. Mineral oils seldom have a viscosity index over 100 unless an improver has been added. High-molecular-weight polymers are added for this purpose.

Pour Point Depressors

Pour point depressants are liquids which are added to wax-bearing oils to lower their pour point. Wax-bearing oils cease to flow when the wax crystallizes to a honeycomb structure. Many pour point depressors have about the same physical characteristics as the oil to which they are added. The lowering of the pour point is not a dilution by a light fraction but is accomplished by preventing the wax crystals from joining together into a lattice structure.

Emulsion Breakers

An emulsion of oil and water is invariably caused by a third agent, which may be oxidized oil, iron rust, metallic soaps, or contamination with grease or other foreign substances. As a rule the average emulsion can be broken by heating to 170 to 212° F and then allowing it to settle in a tank or by employing a centrifuge. Some emulsions cannot be broken by this method, and chemical compounds have to be used to free the water from the oil.

In steel mills, where large circulating oiling systems are extensively employed, an emulsion may be formed with the palm oil used in the rolling. Here the use of a chemical compound is frequently required to disintegrate the emulsion.

There are several different types of emulsion breakers, and they are rather selective. Hence the particular emulsion is first of all tested by trial and error until the correct compound is found. The chemical compounds employed to break emulsions are soluble in water, and therefore very little remains in the oil after it is separated from the water. The amount added is usually not more than 0.1 per cent. In fact, if too much (emulsion breaker) is added the result can be a still more stubborn emulsion. The use of these compounds requires considerable experience.

10

Physical Tests

Little is actually known about the chemistry of oils. Therefore, no laboratory test or combination of tests should be considered as a definite indication of suitability for lubricating oils. Laboratory tests are a guide to results that may be anticipated in practical service, but they are not a guarantee. For purchase control purposes tests are equally valuable, but they must be used with discretion and reasonable understanding. No single test is of itself particularly significant in evaluating a lubricant. A suitable combination of tests will indicate that an oil should be satisfactory for a specific application. The reason that we can use a few simple common tests for most applications is that all refiners are constantly striving to produce even better lubricants than are now available.

In this chapter we shall describe and discuss physical tests which have been found useful in the application of oils. Those interested in the details of the test apparatus and procedures for fuels and lubricants should refer to the American Society for Testing Materials (A.S.T.M.) for standards.

Viscosity

Viscosity is a measurement of a liquid's internal resistance to flow, and is the most important single property of lubricating oils. The viscosimeter is to the oil man what the ruler is to the carpenter. Viscosity determines the ability of an oil to support a load on a fluid film, the power consumed in friction, and the amount of heat that will be generated.

The Saybolt universal viscosimeter is used in the United States to determine viscosity, as it is a simple form of apparatus and gives reliable results for comparative purposes. The principal sections of the apparatus are outlined in Figs. 1 and 2. The top receptacle is filled with the oil to be tested until it overflows the rim. This is slightly over 60 cc. The apparatus is in a heat bath held at either 100 or 210° F, for whichever temperature it is desired to obtain the viscosity. Light oils are run at 100° F, and heavy oils at 210° F. When the oil has reached the temperature of the bath, the plug is pulled out and the time in seconds for 60 cc to run into the flask is recorded as the viscosity. For example, if the temperature of the oil was 100° F and the time taken to fill the flask was 500 seconds, the oil would be said to have a viscosity of 500 at 100° F. This measurement is generally written as follows: viscosity 500 at 100° F (S.S.U.). The S.S.U. indicates that the viscosity was run with a Saybolt universal viscosimeter.

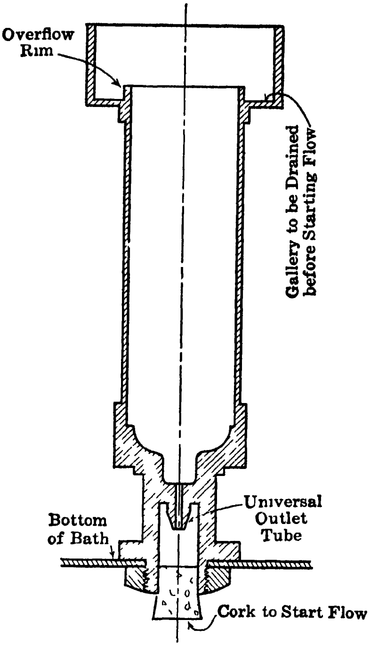


Fig. 1. Sectional view of Saybolt tube for securing the viscosity of lubricating oils.

As a general rule, viscosity readings are taken at 100° F for time limits between 40 and 1000 seconds. Readings below 40 seconds are not sufficiently accurate with this method, and very few types of lubricating oils have a viscosity of 40 seconds at 100° F. This reading is approximately the viscosity of light fuel oil.

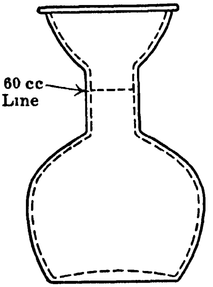


Fig. 2. Saybolt flask.

Readings for more viscous oils are taken at 210° F on the Saybolt universal viscosimeter. For example, if the time taken to fill the lower receptacle with 60 cc was 150 seconds at a temperature of 210° F, this would be written: viscosity 150 at 210° F (S.S.U.).

In general, a short period of time is more conducive to accuracy. A 150 S.S.U. at 210° F might be 3000 S.S.U. at 100° F, which would be 50 minutes for only 60 cc to flow. This is a relatively long time to hold a constant temperature, and it also means inefficient use of equipment.

Viscosity readings may be taken at any temperature. However, a complete test for the great majority of lubricating oils supplies two readings, one at 100° F and the other at 210° F. With two readings, the two points may be joined and extended by a line on a viscosity-temperature chart and intermediate viscosities read off for any desired temperature between. This method of determining viscosity is relatively accurate for most readings between 30° F and 300° F.

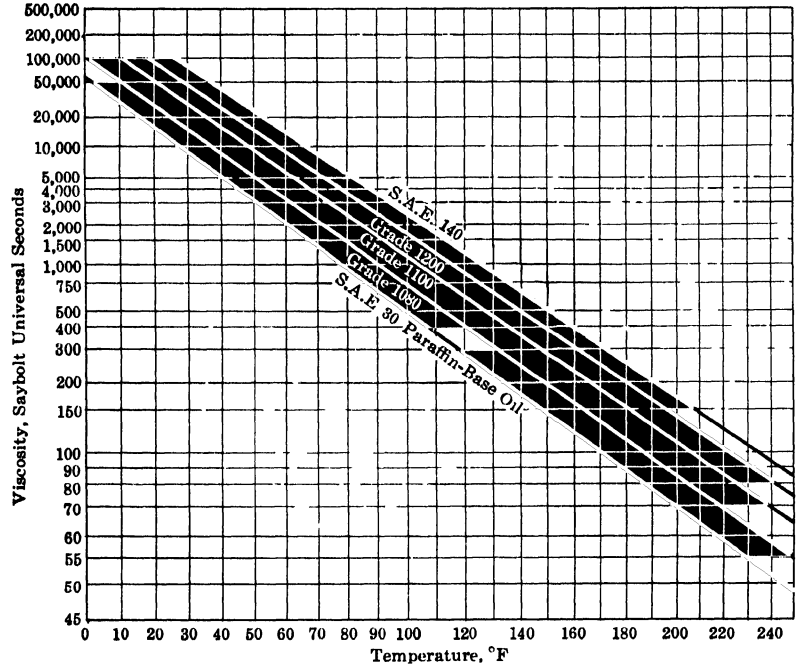


Fig. 3. A.S.T.M. viscosity chart.

Figure 3 shows an A.S.T.M. chart that is sufficiently accurate for almost all purposes. Larger charts with a wider range of temperatures are also available. The lubricating oil viscosities plotted are those of an S.A.E. 30 and three typical aircraft-engine oils with their grade number, which is their approximate viscosity at 210° F.

This chart shows what happens to an oil with a change in temperature. In the higher temperature range the viscosity of the oil is cut just about in half for each 70° rise. At ordinary room temperatures the viscosity is cut in half for each 15° rise. The log-log scale on the chart permits the viscosity change to be plotted as a straight line. This rapid increase in viscosity at lower temperatures explains why in winter a temperature drop of a relatively few degrees makes it very difficult to start a car.

In other countries the same method is employed to measure viscosity, but the instruments vary in minor details. The most popular types are Redwood, Barbey, and Engler, and conversions may be made from a prepared table to Saybolt viscosity, or vice versa. These tables will be found at the end of this book. The table, made from an A.S.T.M. chart, shows the viscosity of various oils at intermediate temperatures. Each viscosity reading at 100° F and 210° F was marked on the chart, then joined and extended by a line to secure the readings shown.

TABLE SHOWING SOME AVERAGE OIL VISCOSITIES AT VARIOUS TEMPERATURES

			Saybolt Viscosity at			
S.A.E. No.	*−30° F*	*0° F*	*100° F*	*210° F*	*300° F*	*400° F*
Transformer Oil	4500	800	55	34		
10		8,500	180	46	35.8	
20		50,000	300	49	36.0	
30		90,000	530	66	41.0	
40			750	76	43.5	
50			1050	90	46.5	36.5

This table is also interesting because it shows how the viscosity of an oil changes with temperature. At low temperatures the light oils do not change very rapidly in viscosity as the temperature drops. This is particularly noticeable in the very light oils, such as transformer oil. At temperatures in the vicinity of 300° and 400° F the light oils reach their initial distillation points.

Notice how the heavier oils tend to reach a common viscosity as the temperature rises. For example, at 400° F the difference between the S.A.E. 30 oil and the S.A.E. 50 oil is only 5½ seconds. This difference remains practically constant until the oils reach their initial distillation points, which occur between 450° F and 530° F for the last three examples.

The effect of temperature on mineral oils may be plotted on squared paper, as shown in Fig. 4. Notice how rapidly the oils thin out as the temperature rises. In this connection it is generally assumed that a viscosity of about 55 seconds Saybolt is the minimum safe limit to support fluid oil films that will prevent metal-to-metal contact between rubbing surfaces.

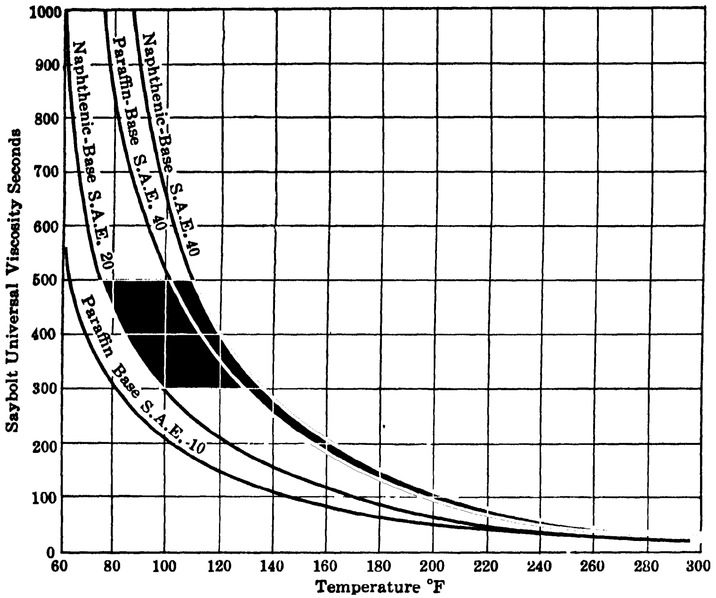


Fig. 4. Lineal viscosity chart.

Saybolt Furol

Saybolt furol viscosity is measured in the same apparatus with a larger capillary. This capillary enables heavy petroleum products to be measured in a reasonable length of time. Saybolt furol seconds multiplied by 10 gives the approximate Saybolt universal seconds of the fluid.

Kinematic Viscosity

Kinematic viscosity is based on "absolute viscosity," which is a mathematical calculation for moving gases and liquids. Some of the units employed are named after the men who worked out these theoretical flow problems in the field of science. However, this text is concerned with the practical results secured rather than with the derivation of mathematical formulas. In actual practice, the kinematic viscosity of a lubricating oil is secured in exactly the same manner as Saybolt viscosity, and each new instrument is calibrated by means of reference liquids, generally distilled water.

Kinematic readings are more accurate than Saybolt readings, particularly in the lower viscosity ranges. This is another reason why kinematic viscosity is generally secured in petroleum laboratories and then converted to Saybolt viscosity. Conversion tables and formulas will be found at the end of this book.

The unit of absolute viscosity is called a "poise" from the name of the physicist and experimenter Poiseuille. One poise is the viscosity of a fluid requiring a shearing force of 1 dyne per square centimeter to maintain a rate of shear equal to 1 centimeter per second per centimeter of lamina thickness; thus:

$$1 \text{ poise} = \frac{1 \text{ dyne} \times \text{second}}{\text{cm}^2}$$

$$1 \text{ centipoise} = \frac{1 \text{ poise}}{100}$$

The reader should not feel discouraged at this point. The poise is based on the theoretical consideration that when a liquid is forced through an orifice the individual layers of molecules slide over each other, and a shearing force is produced by the resistance to flow. This consideration is perhaps more obvious in a bearing where one layer of oil sticks to the bearing surface, another to the revolving shaft, and the layers between are being sheared.

The assumption that the individual layers behave in a uniform manner is purely theoretical. The instruments can easily be calibrated with a reference fluid such as distilled water. Viscosity readings in poise units are secured with instruments which maintain a pressure on the liquid. This calls for delicate adjustments, and hence gravity-flow instruments are preferred. When using gravity-flow instruments one must take into account the specific gravity of the liquid, as this will affect the rate of flow through the orifice. Here we arrive at the unit called a stoke, which is the basic unit of kinematic viscosity. The word "stoke" is derived from the name of another physicist and experimenter, Sir George Stokes.

$$1 \text{ stoke} \times \text{density} = 1 \text{ poise}$$

To avoid decimal points when working with most lubricating oils the viscosity is generally expressed in centipoises or centistokes, which values are one hundredth the poise and the stoke.

$$1 \text{ centistoke} \times 100 = 1 \text{ stoke}$$

$$1 \text{ centipoise} \times 100 = 1 \text{ poise}$$

Density is the weight of unit volume. Specific gravity is relative weight in comparison with some reference substance. If the reference substance is water at 4° C, then specific gravity is numerically the same, and the two may be used interchangeably.

These units and their derivations can be explained in detail only by mathematical equations which are somewhat lengthy and not of sufficient importance in a text concerned with the practical application of laboratory tests. Kinematic viscosity readings are secured from flow instruments, and the operator requires no knowledge of mathematics to interpret the readings. Kinematic viscosity readings have the advantage of being international in scope and understanding, because they can be converted into the poise so easily. There are many types of kinematic viscosimeters, but they all operate on the same principle. Figure 5 shows the construction of the Ostwald instrument.

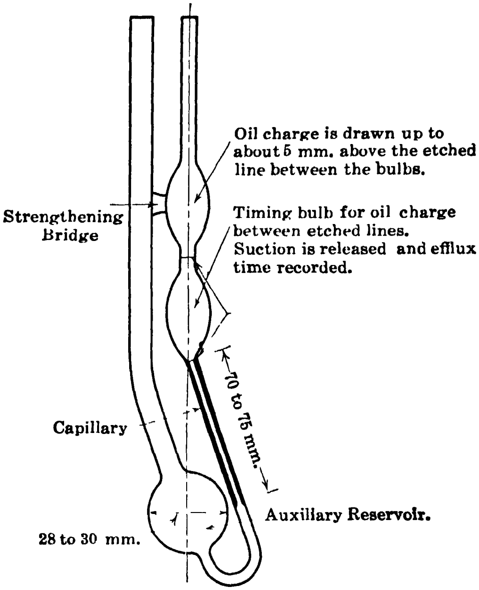

Oil charge is drawn up to about 5 mm. above the etched line between the bulbs.
Strengthening Bridge
Timing bulb for oil charge between etched lines. Suction is released and efflux time recorded.
70 to 75 mm.
Capillary
Auxiliary Reservoir.
28 to 30 mm.

FIG. 5. Oswald kinematic viscosimeter.

In practice a bulb is loaded with oil and the charge is allowed to run out, just as in the Saybolt instrument. The time is recorded in seconds and converted to kinematic viscosity by means of tables. By selecting instruments with different sizes of orifices and bulbs it is possible to run light and heavy oils through in about the same time. Thus this is a rapid means of determining viscosity, as one requires only the table for each orifice size in order to find the kinematic viscosity. Each kinematic viscosimeter is calibrated against a known reference fluid. Kinematic viscosity may be converted to Saybolt viscosity, and vice versa, by a mathematical formula.

The student or lubrication engineer who is interested in design and engineering aspects must make a thorough study of viscosity. The true function of viscosity in lubrication is either not too well understood or else it is neglected by many of those interested in lubrication. It will undoubtedly continue to be so just as long as we use "Saybolt" as an easy way to give some sense of viscosity, and "kinematic" viscosity in stokes multiplied by the density to give absolute viscosity in "poises," which is in the centimeter-gram-second system. We still cannot use viscosity for engineering purposes until we convert it to the pound-foot-second system. Units of measure in this system are the "reyn" (abbreviation for Reynold) and the "newt" (a millionth of a pound per foot per second and an abbreviation for Newton).

Viscosity Index

Viscosity index (V.I.) is valuable for expressing the relative change in viscosity with temperature. The viscosity of petroleum oils changes rapidly with change in temperature, as already shown in Figs. 3 and 4. This rate varies with different types of oil. Naphthenic oils thin out more rapidly than paraffin-base oils as the temperature rises. Conversely, naphthenic oils thicken more rapidly as the temperature drops. To measure this relationship, an arbitrary system of comparison, termed a viscosity index (V.I.), is employed.

The standard of comparison is based on Pennsylvania reference oils refined by the sulfuric acid method and certain Gulf Coast oils refined by the same method. When the system was originally devised, Pennsylvania oils thinned less rapidly than all other types of mineral oils when subjected to heat. They were rated 100 for this property. Gulf Coast naphthenic-base oils were rated 0. Owing to changes in refining methods some Pennsylvania oils may have a V.I. slightly above 100, and some Coastal oils below 0.

The arbitrary basis for securing viscosity index is shown on Fig. 6. The three lines in this viscosity-temperature chart are designated *L*, *U*, and *H*. The Saybolt viscosity of each oil has been recorded at 100° F and 210° F, and then joined by a line on a viscosity-temperature chart. *L* is a naphthenic-base acid-refined reference oil of 0 viscosity index. *H* is a paraffin-base, acid-refined reference oil of 100 viscosity index. *U* is an oil of unknown viscosity index. The viscosity index of *U* is expressed by the percentage difference in slope at 100° F as follows:

$$\text{Viscosity index for } U = \frac{L - U}{L - H} \times 100$$

$$\text{Viscosity index for } U = \frac{420 - 340}{420 - 260} \times 100 = 50$$

This system was originally devised by Davis, Lapeyrouse, and Dean in 1932, and with modifications the method has remained as a standard of comparison since that time.

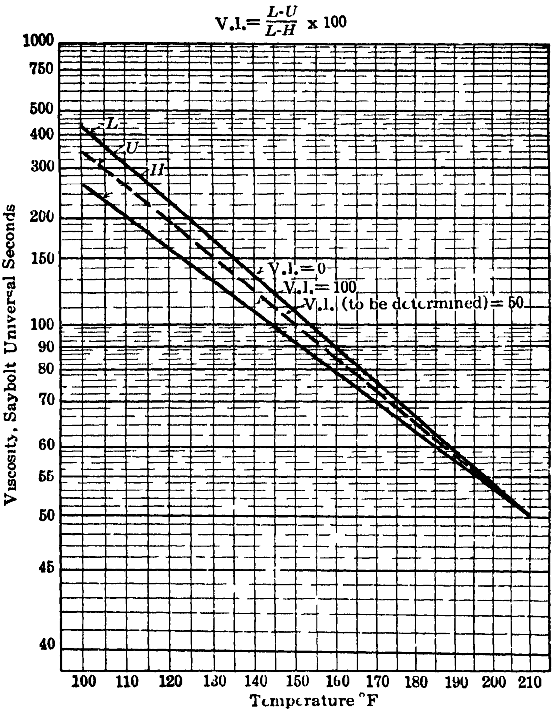


Fig 6 Arbitrary method for securing the viscosity index of a lubricating oil.

An artificial method of improving the viscosity index consists in adding high-molecular-weight polymers derived from petroleum to the oil. Only a small amount need be added to completely change the viscosity index of any lubricating oil. However, the change is most pronounced when the polymerized product is added to light oils. In fact, compounds of this type are capable of raising the V.I. as much as 75 points. Such products change their characteristics at high temperatures.

Considering all factors, such as different refining methods and different blends, the viscosity index reading of an oil is valuable for

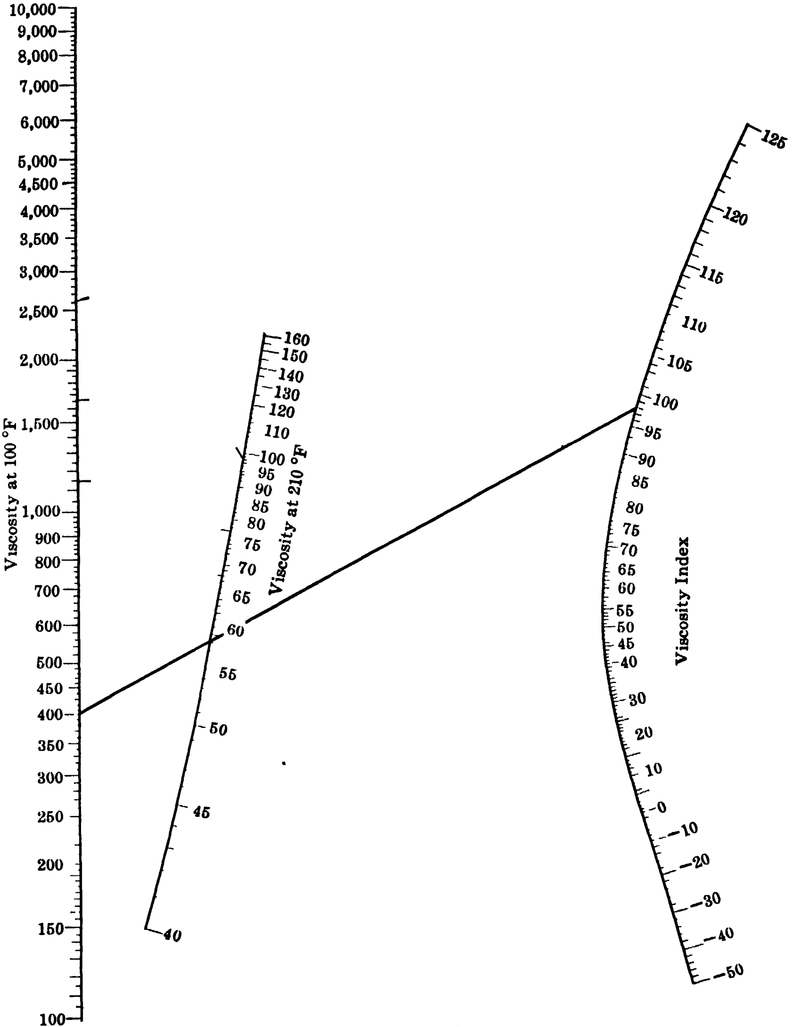


Fig. 7. Viscosity index chart.

expressing the relative change in viscosity with temperature. Viscosity index also provides a rough idea of whether the original crude was paraffinic, mixed-base, or naphthenic in structure, provided of course that no special means were employed to artificially raise the number.

Viscosity index is easily found on a prepared chart which is based on original reference oils. The example shown on Fig. 7 is for a paraffin-type lubricating oil. The viscosity readings were taken at 100° F and 210° F. These two points were joined by a straight line and the line extended to cut the V.I. scale, which gave a rating of 98. Any combination of viscosity readings at two different temperatures will locate the V.I. on this type of chart.

Another method is to use a set of prepared tables for locating the V.I. of a particular oil. These tables give viscosity readings from which corresponding V.I. ratings may be directly checked off. They are published by the American Society for Testing Materials.

The following table gives a few examples of viscosity index ratings for nonadditive mineral oils. Notice that all the examples have a common viscosity of 375 seconds at 100° F. Higher and lower V.I. ratings can of course be obtained. The following table shows an interesting analysis of two oils which have a common viscosity of 250 seconds at 100° F. However, one has a high V.I. of 103, and the other a low V.I. of 18. At a temperature of 0° F the low V.I. oil would take about 50,000 seconds, or some 14 hours, while the high V.I. oil would require only 16,000 seconds, or 4½ hours, to run into the flask. Thus the difference in flowing ability is considerable at low temperatures. At high temperatures there is no significant difference in the viscosity of high or low V.I. oils. All ranges of viscosity index are used in industrial and marine lubrication.

Source of Crude	*Viscosity (S.U.V.) 100° F*	*Viscosity (S.U.V.) 210° F*	*V.I.*
Pennsylvania	375	58	105
Mid-Continent	375	56	94
East Texas	375	54	78
California	375	52	57
Gulf Coast	375	50	28

	Saybolt Viscosity Seconds at				
V.I.	*250° F*	*130° F*	*100° F*	*32° F*	*0° F*
103	42	128	250	2800	16,000
18	38.5	115	250	5000	50,000

Flash and Fire Points

The flash point of an oil is the temperature to which it must be heated to give off sufficient vapor to form an inflammable mixture with air. In this test the vapors flash upon the application of a lighted burner and then go out for want of more vapor. In practical service, this condition would constitute a hazard, owing to the danger of fire or explosion.

The fire point is the temperature to which an oil must be heated to burn continuously after the test burner has béen applied to the escaping vapors. As a general rule this event takes place when the temperature is raised 50° to 75° F above the flash point.

The flash point of an oil is important in determining the type of crude from which the oil was made, the existence of "light ends" which may be present as a result of the blend, or dilution with a liquid of low boiling point. The test is informative in analyzing used oils taken from the crankcases of internal-combustion engines for the reason that, if fuel dilution is occurring, the flash point will be lowered.

Various types of instruments are employed to determine the flash points of petroleum products, but, for lubricating oils, the Cleveland open cup is universally used in the United States. This is a simple open cup which is filled with oil and heated at a uniform rate over a burner. From time to time a small gas burner is applied to the escaping vapors until a flash occurs and then goes out. The temperature at which this event takes place is the flash point of the oil.

The following flash and fire points are representative for a few different types of lubricating oils:

S.A.E. No.	*Crude*	*Flash Point, °F Open Cup*	*Fire Point, °F Open Cup*
30	Pennsylvania	450	510
30	Mid-Continent	430	490
30	California	400	450
30	Gulf Coast	380	430
50	Pennsylvania	520	595
50	Mid-Continent	500	575
50	California	460	535
50	Gulf Coast	440	490

The following are the average open-cup flash points for some petroleum products of different types:

Gasoline	Below 0° F
Cleaning naphtha	110 to 115° F
Kerosene	115 to 150° F
Light mineral oils	325 to 400° F
Heavy mineral oils	400 to 500° F
Cylinder stocks	500 to 625° F

The flash point of a petroleum product varies with the apparatus employed to make the test. For this reason it is necessary to specify the apparatus, but for mineral oils the open-cup method is standard in the United States.

Neutralization Number

The neutralization-number test is a simple procedure for determining the acidity or alkalinity of an oil. It is the weight in milligrams of potassium hydroxide required to neutralize the acid content in 1 gram of oil. The common abbreviation for this test is written mg KOH.

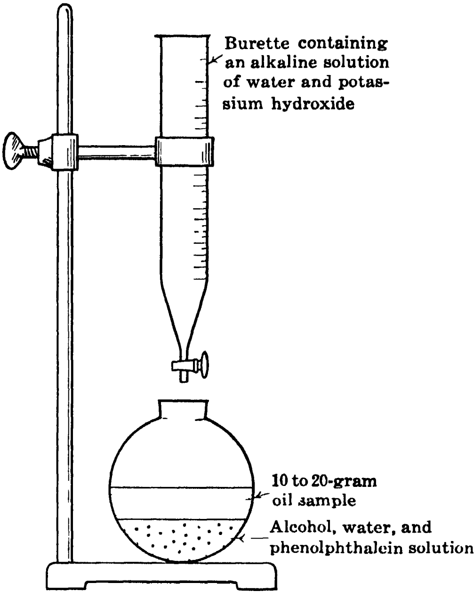

Burette containing an alkaline solution of water and potassium hydroxide
10 to 20-gram oil sample
Alcohol, water, and phenolphthalein solution

FIG. 8. Apparatus for obtaining neutralization number.

Lubricating oils containing detergents may register on the alkaline side, in which case the test is recorded as alkaline neutralization. The test is carried out by measuring 10 to 20 grams of oil into a beaker. A mixture of alcohol, distilled water, and phenolphthalein is added. The phenolphthalein is a color indicator which registers pink when an acid has been neutralized by a hydroxide. Figure 8 shows the apparatus for this test.

When nonadditive oils are new they generally have an acid number less than 0.10, but additive or compounded oils containing such products as detergents, rapeseed, tallow, etc., may have neutralization numbers as high as 3.0 or more. Any neutralization number above

0.10 in a new oil indicates that the oil contains an additive. Some additives have values below 0.10, which, of course, will not affect the acid number of a new oil. The examples in the following table give a very general approximation of the values to be expected in new oils of various types.

Type of Oil	*Neutralization Number*
Medicinal white oils	0.00
Turbine grade oils	0.01 to 0.06
Machine oils (clear colored, straight mineral)	0.05 to 0.10
Marine engine oils (15 to 20% rapeseed oil)	1.00 to 3.00
Detergent-type internal-combustion engine oils	0.50 to 1.50

In actual service, all lubricating oils tend to combine chemically with oxygen and form petroleum acids. The rate of change depends upon the factors present to accelerate the action. For example, heat is easily the most active agent in hastening the oxidation of oil, just as moisture will influence the oxidation of iron and hasten the process of rusting. A change in the neutralization number of an oil in service indicates that chemical changes are occurring in the oil. The permissible amount of change that can be tolerated can be determined only by experience with a given oil. The type of crude and the refining and service conditions are all factors that affect an oil's performance. The acidity test does not distinguish between corrosive and noncorrosive acids, nor does it distinguish between other types of compounds that have an acid reaction. These compounds may be harmful or beneficial. All this indicates that considerably more than just the neutralization number must be known about an oil.

The presence of excessive organic petroleum acid, or similar product of oxidation, can generally be detected by the odor of the used oil. Instead of the familiar and rather pleasant odor of new oil, the odor is pungent and acetic. However, the odor test can only be used as a rough guide on samples which are free from gasoline or similar contaminants. Scenting agents of this type are capable of smothering the delicate sense of smell.

Saponification Number

The saponification number is the number of milligrams of potassium hydroxide needed to saponify 1 gram of oil. When a hydroxide is added to fat or fatty acid under suitable conditions, a soap is formed by the reaction. Under the A.S.T.M. rules of procedure the complete saponification test is more than just the mixing of the two liquids; the purpose is to identify animal and vegetable oils or to determine the quantity of fatty material in compounded oils. The test may also be applied to straight mineral oils, new or used.

When applied to mineral oils, the test determines the presence of fatty acids or any other saponifiable materials which may be present in minute quantity.

The presence of fatty acids in used oils may be the result of oxidation, catalytic action, or other cause, and the test is often carried out on transformer oils and circulating oils where materials of this type may have formed after long periods of service. The actual identification of these materials is often very difficult, and sometimes considerable research work is required in making a complete analysis.

The saponification numbers for various refined animal and vegetable oils are as follows:

Fatty Oil	*Saponification Number*
Lard oil	192 to 198
Tallow	193 to 198
Neat's foot	193 to 204
Fish	140 to 193
Sperm	120 to 140
Castor	176 to 187
Rapeseed	170 to 179
Soybean	189 to 197
Peanut	186 to 197
Cottonseed	191 to 197
Blown rapeseed	195 to 216
Blown cottonseed	210 to 225
Degras	110 to 210

It will be noted that many of the fatty oils have the same saponification number range. It is therefore necessary to know the fat in order to determine the percentage of compounding in an oil.

If it is desired to find the percentage of fatty oil in a compounded mineral oil the following procedure may be used:

$$\text{Percentage of fatty oil} = (C/F) \times 100$$

where C = the saponification number of the compounded oil and F = the saponification number of the fatty oil.

As an example, the saponification number of a steam cylinder oil compounded with tallow might be about 12. By substitution in the formula,

$$\text{Percentage of fatty oil} = \tfrac{12}{195} \times 100 = 6\% \quad \text{approximately}$$

Aniline Point

To determine the relative amount of paraffinic constituents in petroleum liquids, the sample to be tested is mixed with an equal volume of aniline. The mixture is gently heated and agitated in a test tube until complete miscibility is secured. At this point the temperature in degrees Fahrenheit or Centigrade is noted and recorded as the aniline point.

This test has little value when applied to mineral oils but has some value when applied to fuels for internal-combustion engines.

For an example of the use of the aniline point, refer to the "Diesel Index" section in Chapter 11. This test forms the basis of calculations for determining the ignition quality of Diesel fuel.

Iodine Number

The iodine number of an oil is an indication of its drying properties. The test is carried out under prescribed conditions. In this test the amount of iodine absorbed by an oil is expressed as a percentage, and the test figure gives a clue to the relative drying property of the oil. The following are approximate iodine numbers for well-known oils which have been refined for use in compounding with mineral oils.

	Iodine Number
Linseed	160 to 200
Corn	110 to 120
Rapeseed	80 to 110
Blown rapeseed	50 to 70
Castor	80 to 90
Sperm	80 to 85
Olive	75 to 95
Lard	60 to 80
Tallow	60 to 70
Mineral oils	9 to 16
Paraffin wax	4 to 6

These tests are of academic value only, for the reason that oils which dry rapidly, such as linseed oil, are obviously not suitable for compounding with lubricating oils. As a general rule, oils which have values above 100 are not used for compounding with mineral oils. Oils with high aniline point and high iodine number have the least harmful action on natural rubber.

Unsulfonated Residue

This test is applied to mineral oils that are to be used as a base for plant spray oils. The test determines the amount of unsulfonated residue in the oil.

The test is carried out by mixing 5 milligrams of the mineral oil with 4.5 milligrams of specified sulfuric acid in a graduated glass bottle, heating and stirring the mixture in a bath to a temperature of 212° F, and then whirling the bottle in a centrifuge for 10 minutes. The heavy sulfuric acid divides the oil into two levels, and the level unaffected by the sulfuric acid is reported as a percentage of the original sample. This percentage is the unsulfonated residue. The balance of the oil has reacted with the sulfuric acid to form sulfonates. Medicinal white oils which are refined by treating oil with fuming sulfuric acid are thus unaffected by the action of sulfuric acid and have a value of 100. Other oils less highly refined have a value as low as 80.

Sulfur Test by Bomb Method

This method of test is intended for use in the determination of sulfur in petroleum oils. The test determines the total amount of sulfur in a sample of oil. Hence, if the oil tested is a cutting oil to which sulfur has been added, the test determines the amount of sulfur that may have been added as well as the amount of sulfur that was originally in the oil. No satisfactory test has been developed to distinguish between natural sulfur and added sulfur in cutting oils.

In this test the oil is placed in a sealed bomb and burned in the presence of oxygen. By means of a chemical analysis the amount of sulfur is determined from the products of combustion and reported as a percentage of the original sample.

Copper Strip Test

To determine whether or not a petroleum product contains corrosive or tarnishing material, a polished copper strip is submerged in the oil at a specified temperature for a given time. If the product contains any trace of an agent that is chemically active with copper, the copper strip becomes discolored. The copper strip test may be applied to any type of lubricating oil, new or used, straight mineral or compounded. The results are generally reported as negative, slight discoloration, etc.

Discoloration of a copper strip does not always mean that sulfur or sulfur compounds are present. *The test does not identify the item or items which may be producing the tarnish or corrosive action, nor does it indicate their possible degree of corrosiveness on other metals and alloys.* However, it may be stated that all properly refined straight mineral oils and the great majority of compounded oils are generally noncorrosive if they withstand the copper strip test. That is, the test is a guarantee against the possible presence of corrosive ingredients.

Sulfur is an element which is always present in petroleum oils, and its harmful compounds have to be removed by refining. There are several forms of sulfur compounds, such as hydrogen sulfide and sulfur dioxide. These forms are more or less corrosive and attack the copper strip. Other groups known as mercaptans are noncorrosive, but they have an unpleasant odor.

The copper strip test is not particularly well adapted to testing cutting oils but is useful in checking mineral-lard oil blends which may be used for machining copper and copper alloys. When applied to other types of cutting oils containing sulfur, chlorine, phosphorus, etc., the strip will generally show discoloration; but the degree of discoloration is sometimes a useful comparison, particularly when the use of these more active types is contemplated for machining metals that are easily tarnished, or when tarnish is an important factor owing to a later process of plating, tinning, etc. In this connection, cutting oils with properties that will only show a very slight discoloration of the strip are obtainable.

Specific Gravity

The specific gravity of a mineral oil is a numerical value, an index of the weight of the oil compared with the weight of an equal volume of water. Water is given a unit number of 1; all liquids with a reading below 1 are lighter than water, and all liquids with a reading above 1 are heavier than water.

The specific gravity of an oil is, in the United States, the ratio of the weights of equal volumes of oil and water, both weights being determined with the liquids at a temperature of 60° F (15.56° C) and both weights being corrected for the buoyant effect of air. The temperature limitations are indicated conveniently by the expression "specific gravity 60/60° F."

European practice in reporting specific gravity differs from that of the United States. The custom in Europe is to report the ratio of weights of equal volumes of oil and water, the oil at a temperature of

15° C (59° F) and the water at a temperature of 4° C (39.2° F). The weights are not corrected for the buoyant effect of air. According to this system the weight of a specified volume is directly proportional to the specific gravity of the oil. When specific gravities are reported according to the United States system, it is necessary to use the tables published by the Bureau of Standards to calculate the weight per gallon of oils of different A.P.I. and specific gravities. Light petroleum products are frequently sold on the basis of volume delivered, corrected to 60° F from the original temperature of measurement. This volume correction is made by the use of approved tables. The property of gravity is of importance in the control of refinery operations, or where large volumes of oil are being handled. Gravity is also important in converting kinematic to absolute viscosity. The test is quickly and easily made and furnishes information which is useful for process control. It is also helpful in identifying unknown oils because the gravity of an oil gives a clue as to the type of crude from which it was manufactured. For example, paraffin-base oils run lower in specific gravity than do coastal oils. Examples are given in the table in the following section.

Gravity, A.P.I.

Specific-gravity readings are given several places to the right of the decimal point, as 0.9765. The American Petroleum Institute (A.P.I.) has devised a simpler method which eliminates decimal points. The readings are taken at 60° F and given as 10, 11, 12, etc., or fractions thereof.

Gravity A.P.I. is determined by a method similar to specific gravity, wherein a unit volume of oil at a temperature of 60° F is compared with the weight of an equal volume of water at 60° F and expressed as a ratio. However, the A.P.I. hydrometer is adapted to the simplified numerical system and starts at 10, which is equivalent to 1 for the unit specific gravity of water at 60° F. Conversion tables from one system to the other will be found at the end of this book. The gravity tests in the table were carried out on a number of representative motor oils. Notice that the two scales run in opposite directions; the heavier the oil, the lower the A.P.I. gravity; on the other hand, the heavier the

S.A.E. Number	*Crude*	*Gravity A.P.I.*	*Specific Gravity*
30	Pennsylvania	29–32	0.8654–0.8816
30	Mid-Continent	28–30	0.8762–0.8871
30	California	23–27	0.8927–0.9159
30	Gulf Coast	18–23	0.9159–0.9465

oil, the higher the specific gravity. The A.P.I. gravity in the table ranges from 18 to 32, or 14 whole numbers, while the specific gravity ranges from 0.8816 to 0.9465, or a total of 0.0649. It can thus be seen why it is easier to recognize significant differences in gravity when using the A.P.I. system. The A.P.I. gravity of an oil is a mathematical function of specific gravity. The relationship is indicated by the following equation:

$$\text{Gravity, A.P.I.} = \frac{141.5}{\text{Specific gravity } 60/60^\circ \text{ F}} - 131.5$$

The figure 141.5 is termed the modulus of the A.P.I. scale.

Pour Point

The pour point of an oil is an indication of its ability to move at low temperatures. The test is important for lubricating oils that are to be used in cold surroundings, particularly where they must flow to the suction side of an oil pump.

The test procedure is very simple and consists in freezing the sample in a test tube until the oil ceases to pour, then adding 5° F to the freezing temperature. For example, if a particular grade ceases to pour at 10° F the pour point would be specified as 15° F.

The pour point of an oil does not take into consideration the characteristic of pumpability. When lubricating oils are pumped through bearings under low-temperature starting conditions the paraffin-type lubricating oils generally pump more easily than other types with similar pour points. However, the pour point reading is very important for lubricating oils that are to be used in all types of engines and machines that are operating in cold surroundings.

The pour point of an oil should not be relied upon entirely for low-temperature operation because the value is more of a guide than a definite guarantee of practical flowing ability. For example, a study of the following comparisons will demonstrate this feature.

	Approx.	*Gravity*	*Saybolt Viscosity at*			*Pour*
Example	*S.A.E. No.*	*A.P.I.*	*210° F*	*100° F*	*0° F*	*Point*
Oil A	10	23	44	200	20,000	0° F
Oil B	40	22	62	700	300,000	0° F

The above oils A and B are of the naphthenic type and both have a pour point of 0° F. However, oil A would obviously function much better than oil B at low temperatures because it is much lighter. Probably some time would elapse before oil B would warm up to a suitable flowing temperature, and damage to machinery would result in the meantime. At a temperature of 0° F oil A has a viscosity of 20,000 seconds and oil B has a viscosity of 300,000 seconds; hence there is a marked difference in the characteristics of the two oils, and, while both may actually move in a test tube at 0° F, there is a vast difference between the viscosity readings or flowing speeds.

This comparison may be brought out more clearly if the viscosity readings are converted to hours instead of seconds. For example, 60 cc of oil B would require about 83 hours to run out of the Saybolt instrument at 0° F. Oil A would require about 8 hours.

Therefore, when considering an oil for low-temperature operating conditions, the viscosity at the anticipated lowest starting temperature is very important. For example, if an oil was being selected for the bearings in a deep well pump, the temperature of the water would be an important factor because it would influence the viscosity of the oil.

Cloud Point

The cloud point of a petroleum oil is the temperature at which paraffin wax or other substances begin to crystallize or separate out from solution when the oil is chilled. This test is sometimes applied to refrigeration oils.

Pumpability of Lubricating Oils

There is no standard test to denote the ability of a particular oil to pump readily at low temperatures. However, it may be stated that, at low temperatures, paraffin-base oils will flow through a pump more readily than naphthenic-base oils, all other conditions being equal or nearly equal.

This difference is due to the fact that paraffin-base oils exhibit less change in viscosity with change in temperature, but in a laboratory test tube the wax crystals form at low temperatures and prevent flow. For example, the table gives a comparison between two oils and is based on a practical experiment with a standard type of small pump and piping such as that used in the average circulating oiling system. Notice the vast difference in viscosity at 0° F between the two oils. Another consideration is that the resistance to flow requires more engine power, so that sometimes there is insufficient power to start. The ability of the paraffin-base oil to flow at 0° F was due to the fact that the pump plunger merely broke up the wax crystals which had formed at low temperature in the paraffin-base oil, and once the honeycomb

Type of Oil	*Approx. S.A.E. No.*	*Gravity A.P.I.*	*Saybolt Viscosity at 210° F*	*100° F*	*0° F*	*Pour Point*	*Pump-ability at 0° F*
Paraffin base	30	29	69	550	60,000[1]	10° F	Slow
Naphthenic base	30	20	57	570	250,000	−10° F	Slower

[1] Extrapolated on an A.S.T.M. viscosity-temperature chart. The experiment showed that while the paraffin-base oil had a higher pour point, namely 10° F compared with −10° F for the naphthenic oil, it nevertheless pumped more readily at 0° F.

structure had been disrupted by agitation and vibration in the suction line the oil was able to flow.

The assumed viscosity of the paraffin-base oil at 0° F was secured by the use of an A.S.T.M. viscosity-temperature chart, and the laboratory pour point was of course ignored because at 0° F the paraffin-base oil had ceased to register any ability to flow in a test tube. Nevertheless, at low temperatures it pumped just as readily and faster than the naphthenic-base oil, which had a pour point that was 20° F lower. At −10° F both oils failed to pump because they had congealed and had become too viscous to flow into the suction line.

In the planning of oil transfer lines from bulk storage, the heating coils in the installation should be arranged to provide a Saybolt viscosity of about 200 to 500 seconds at pump suctions. This precaution will assure the reasonable flow of all grades to their destination.

Color

Color requirements for lubricating oils are frequently overemphasized. Color is not always an indication of quality, nor is a pale color indicative of low viscosity. Darkening of an oil in service either through oxidation or contamination is more easily detected in a light-colored oil than the darker or black oils.

There are several instruments which determine color by means of transmitted light, and in each the principle employed is that of matching the light passing through a specified depth of oil against a known color.

For color matching in the United States the Union colorimeter is generally employed. Color matching by means of this instrument depends upon passing light from a bulb through a given depth or thickness of oil and comparing the result with various color standards through an eyepiece. If the oil is darker than the darkest color standard, provision is made for measuring the color by diluting the oil with 15 per cent of kerosene by volume. The kerosene is specified as not darker than +21 on the Saybolt chronometer, which is employed for matching lighter distillates and white medicinal oils.

The comparisons in the accompanying table are based on tests employing the Union colorimeter for lubricating oils.

A.S.T.M. Union Colorimeter No.	*Approximate Color Match (National Petroleum Association Name)*
1	Lily white
1½	Cream white
2	Extra pale
2½	Extra lemon pale
3	Lemon pale
3½	Extra orange pale
4	Orange pale
4½	Pale
5	Light red
6	Dark red
7	Claret red
8	Almost opaque (nor classified)

White oils of the medicinal type are graduated for color by means of the Saybolt chronometer. The method is based on passing light through the sample and measuring the depth or thickness of oil required to match a standard-color glass. White oils tested by this standard may be whiter than water white, and +30 on this scale indicates a medicinal oil of U.S.P. standard (United States Pharmacopoeia). A reading of 25 on this scale indicates water white. The complete scale is graduated from +30 to −16 and is employed to determine the color of highly refined oils, naphthas, kerosene, gasoline, etc.

Dielectric Strength

Highly refined mineral oils possess excellent insulating properties. They are used as a cooling medium in transformers, oil circuit-breakers, and similar apparatus. There is some interest in this test when oil is used with certain types of refrigerants, such as SO_2.

The resistance to breakdown from an electrical discharge is measured by passing an electrical current through the oil until the voltage is sufficient to cross a gap between two submerged electrodes which are placed 0.1 inch apart. In the United States these discs are circular and have a diameter of 1 inch.

The apparatus, temperature conditions, etc., are standardized, and the breakdown point of the oil is recorded in volts. An average grade of transformer oil will resist 30,000 volts under this test.

When mineral oils are to be used in electrical equipment, they are refined to eliminate all impurities, and special precautions are taken to remove all trace of moisture. An almost infinitesimal trace of moisture will lower the dielectric strength. Figure 9 shows the effect of moisture in transformer oil.

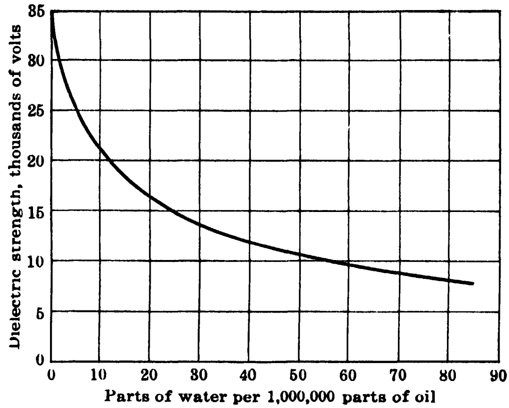


FIG. 9. Effects of moisture on dielectric strength of oil.

Carbon Residue, Conradson and Ramsbottom

Carbon residue tests determine the percentage of carbon that remains in a sample after the volatile vapors have been driven off by means of heat. Figures 10 and 11 show the apparatus employed to carry out this test.

As a guide to possible service performance, the scope of the carbon residue test is somewhat limited. For example, paraffin-base lubricating oils run high in carbon content when judged by this method of test. Yet, they could hardly be condemned for automotive- and aircraft-engine service when their highly successful record is considered.

The test has a relative but limited value when applied to Diesel-engine lubricating oils where the choice of a suitable lubricating oil may be in doubt. However, this type of choice is invariably confined to paraffin-, mixed-base, or naphthenic-type oils, and the naphthenic grades automatically show lower carbon content values. At one time it was thought that the carbon residue test was a guide to the formation of carbon deposits in the cylinders of internal-combustion engines, but this theory has been disproved. One still finds this test in some specifications, however.

When considering carbon content, other factors must also be examined, and, as previously stated in this chapter, the merit of one particular test must be balanced against the merits of several other tests.

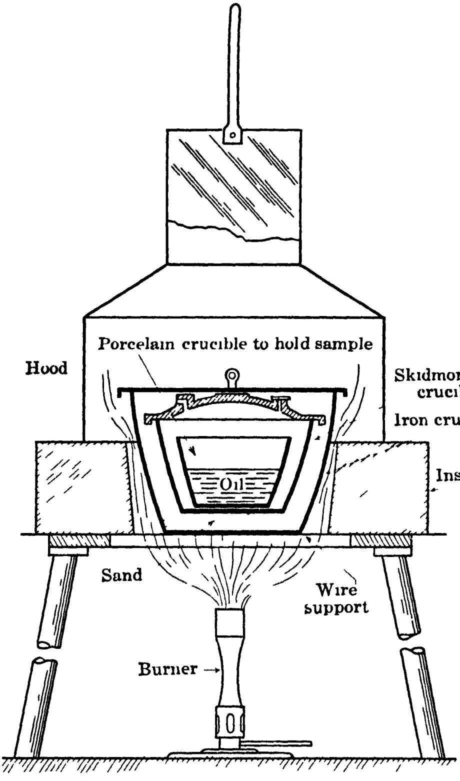


Fig. 10. Apparatus for determining carbon residue (*Conradson*).

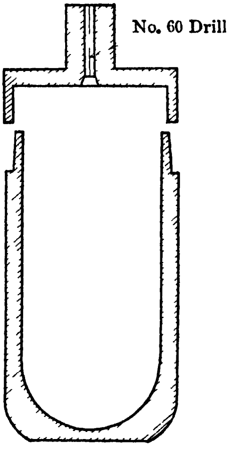


Fig. 11. Bulb for Ramsbottom carbon residue test.

The Conradson carbon residue test is sometimes employed in analyzing used oils taken from the crankcases of internal-combustion engines.

Conradson carbon residue is determined by heating 10 grams of oil in a crucible until the vapors cease to burn and no further smoke arises. At this point the bottom plate is held at a cherry red heat for 7 minutes. When the crucible has cooled, the carbon residue is weighed and calculated as a percentage of the original 10 grams. The total heating time allowed for all grades of lubricating oils is 30 minutes.

Ramsbottom carbon residue is determined in a stainless steel tube or bulb with a small aperture at the top to let the vapors escape. The sample is subjected to a temperature of 1022° F for 20 minutes. Upon completion of the test, the difference in weight of the bulb before and after the test divided by the weight of the sample and multiplied by 100 is the Ramsbottom carbon residue expressed as a percentage of the oil sample.

As a general rule, the amount of carbon residue secured by the Ramsbottom method is lower than the amount secured by the Conradson method. The following are average values issued by the A.S.T.M.

AVERAGE RELATION BETWEEN RAMSBOTTOM AND CONRADSON CARBON RESIDUES, PER CENT

Ramsbottom	*Conradson*	*Ramsbottom*	*Conradson*	*Ramsbottom*	*Conradson*
0.08	0.00	1.00	1.29	2.00	2.86
0.10	0.02	1.10	1.45	2.50	3.52
0.20	0.14	1.20	1.63	3.00	4.17
0.30	0.27	1.30	1.80	3.50	4.81
0.40	0.40	1.40	1.99	4.00	5.44
0.50	0.53	1.50	2.20	4.50	6.08
0.60	0.67	1.60	2.33	5.00	6.70
0.70	0.82	1.70	2.46	6.00	7.90
0.80	0.97	1.80	2.60	7.00	9.10
0.90	1.13	1.90	2.73		

The following are some average carbon residue values obtained by the Conradson method with representative petroleum products. The range for lubricating oils is comparatively wide because the naphthenic oils register low values, and the paraffin oils high values. Two oils of the same viscosity from the same type of crude but having different carbon residue values indicate difference in the degree of refining. The lower value indicates a higher degree of refining.

Gasoline	None
Kerosene	None
No. 2 fuel oil	None to 0.05
Lubricating oils (S.A.E. 30)	0.10 to 1.00
Lubricating oils (S.A.E. 50)	0.30 to 1.60
Steam cylinder oils	1.50 to 4.00

Steam Emulsion Number

This test was formerly of importance as a means of determining whether a steam turbine oil would or would not emulsify in the presence of steam condensate. When used with other tests it may have value, but difficulties in interpreting the significance of a change in the number has caused it to be largely discarded. It may be of value as one of the tests for transformer oils.

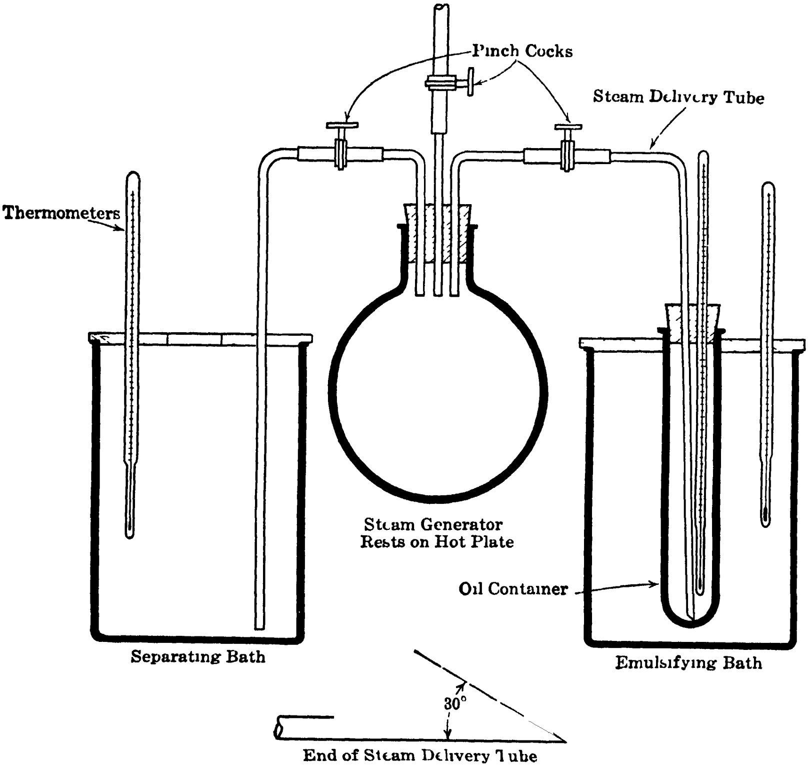


FIG. 12. Apparatus for steam emulsion test, self-generating steam supply.

The test consists of passing steam at 212° F through 20 cc of oil in a test tube for a period of 4 to 6 minutes. The tube is then placed in a bath at 200° F, and the time taken by the oil to separate from the condensed steam is clocked in seconds. The number of seconds taken is the steam emulsion number. Needless to say, this test gives an indication of the ability of an oil to separate readily from water. The test is very sensitive, and once an oil has been circulated through a turbine oiling system the number rises. The ideal steam emulsion number for new oils would be zero or instantaneous separation. Light turbine oils of the straight mineral type will separate in 15 to 25 seconds, medium oils in 30 to 50 seconds, heavy medium oils 40 to 80 seconds, and so on. Figure 12 gives an outline of the apparatus employed. When an oil contains an antirust compound the steam emulsion number will be raised appreciably, so that the test is not valid.

Interfacial Tension

The effect of surface tension is easily demonstrated by filling a glass of water to the brim, then adding more water. This extra water will rise above the level of the brim before it spills over. The effect is produced by the ability of the molecules at the surface to hold together until a certain amount of force is generated to overcome their resistance against parting.

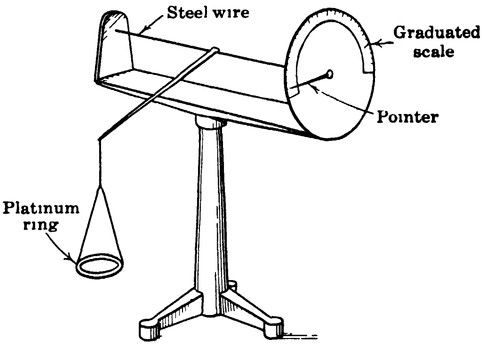


FIG. 13. du Nouy interfacial tension meter.

The surface tension of a liquid may be measured by suspending a platinum ring in the sample to be tested, then pulling the ring upward until it reaches the surface. At this point the force required to break through the surface of the liquid is registered on a torsional spring balance, and the reading is recorded in dynes per square centimeter (see Fig. 13). When distilled water is tested at 75° F the average reading is about 76, which means that a force of 76 dynes per square centimeter is required to break the surface of distilled water. These readings could be recorded in pounds per square inch, but the decimal points would obviously be too unwieldly to work with.

The interfacial tension test is carried out on oils in the following manner: the platinum ring is lowered into a bath of distilled water which is maintained at a prescribed temperature, then a sample of the oil is allowed to spread out on the surface of the water. Because of the fact that organic acids and wetting agents are mostly hydrophilic, which means that they have an affinity for water, they tend to concentrate into a layer of their own at the water-oil interface. (See Figs. 14 and 15.) When the ring is pulled upward, it strikes this interface, and a force is required to break away from the water. A delicate spring balance measures the force in dynes per square centimeter, and the reading is reported as the interfacial tension. When straight mineral oils are tested for surface tension they register 30 to 55. Highly re-

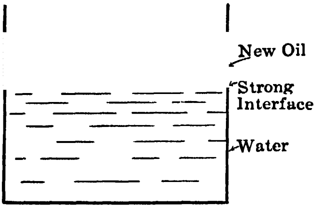


FIG. 14. Showing clear line of demarkation between water and new oil having a high surface tension at the interface.

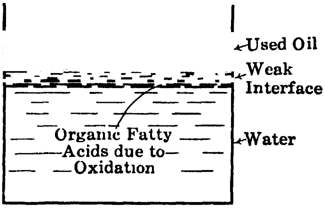


FIG. 15. Showing line of demarkation between water and used oil having a weak surface tension at the interface owing to accumulation of fatty acids.

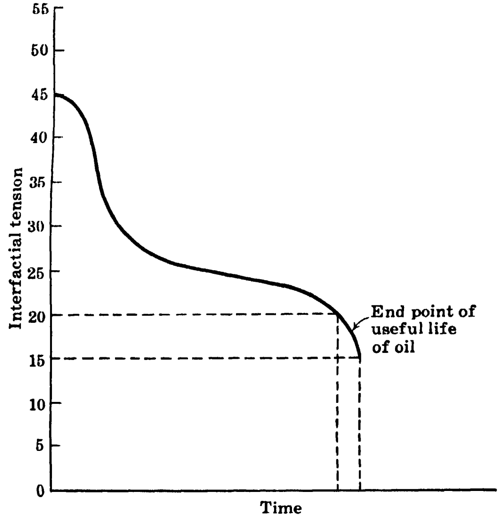


FIG. 16. Useful life curve of an oil as measured by interfacial tension.

fined white oils register 50 to 55, and ordinary machine oils 35 to 45. Oils containing wetting or dispersant agents may have an interfacial tension of 5 or lower. Turbine-grade oils are highly refined products, and as a rule lack wetting ability to prevent rusting. They register a high interfacial tension. Materials are added which cause the oil to wet the metal and tend to prevent rusting in the presence of moisture. These materials lower the interfacial tension of new oil, but the interfacial tension generally rises when the oil is in service, owing to the wetting out of these materials from the oil on the metal surfaces. The test has been of some value in judging the useful life of oils having an initially high interfacial tension. When the I.F.T. of such an oil falls to 20 to 15, it is generally conceded that the oil has reached the end of its useful life. A typical curve of such an oil is shown in Fig. 16.

Oils having an initially low I.F.T. may show an erratic curve owing to the wetting out of the wetting agent on the metal surfaces. This raises the interfacial tension, which will be lowered again as the oil oxidizes. However, the addition of make-up oil will affect the curve and in some oils may prevent the rising of the I.F.T. to a significant point.

Precipitation Number

This test is used primarily to determine the amount of oil-insoluble material in an oil. This test is applied to new cylinder and black oils. The lower the precipitation number, the higher the degree of filtration. For certain types of service there appear to be no detrimental results from using oils of relatively high precipitation numbers, as, for example, railroad-car journal oils, gear shields, etc. Precipitation number is determined by diluting 10 milliliters of oil with 90 milliliters of petroleum naphtha and centrifuging the solution in a cone-shaped tube at 1500 rpm for 10 minutes. The sediment deposited in the tip of the cone is measured and reported as the precipitation number. Figure 17 shows the type of glass bottle used.

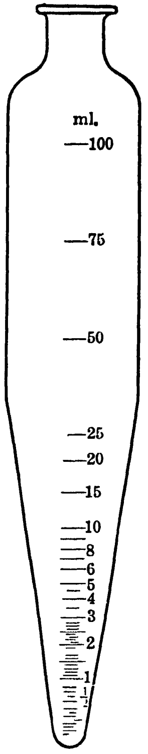


FIG. 17. A.S.T.M. cone-shaped centrifuge tube for securing precipitation number.

For an examination of used oils, the precipitation test is a quick means of determining the presence of foreign materials. For example, the precipitate will disclose the source of contamination, provided its specific gravity is higher than that of the oil and naphtha and that the material is not dissolved in the oil or naphtha.

Foam Test

There is no accepted test for various lubricating oils, except a tentative test for the foaming characteristics of crankcase oils.

A given quantity of the oil to be tested is placed in a graduate and held at a specified temperature. A given volume of air is introduced into the oil through a porous stone diffuser. The volume of foam at the end of a 5-minute period is called the foaming tendency. The volume of foam at the end of a 10-minute rest period is called the foam stability. If the volume after the 5-minute blowing period is less than 10 milliliters the oil is considered nonfoaming. See Fig. 18 for a sketch of the apparatus.

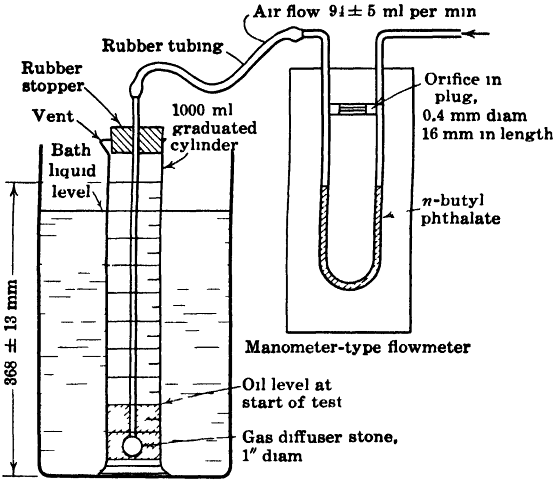

Air flow 94 ± 5 ml per min
Rubber tubing
Rubber stopper
Vent
Bath liquid level
1000 ml graduated cylinder
Orifice in plug, 0.4 mm diam 16 mm in length
n-butyl phthalate
368 ± 13 mm
Manometer-type flowmeter
Oil level at start of test
Gas diffuser stone, 1" diam
Constant-temperature bath

FIG. 18. Apparatus used in foam test.

Naphtha and Benzol Insolubles

An important test carried out on many samples of used oils is that of determining the composition of sludges and solids. The test may be applied to samples taken from the crankcases of internal-combustion engines, transformers, circulating oil systems, and from similar equipment where the information may be considered of importance.

There is no common standard of procedure for this type of analysis. However, the following method is popular, for the reason that the particular solvents mentioned are obtainable in grades which are reasonably uniform. When other solvents are specified, the results secured will be reasonably close, provided the test is carefully carried out and the solvents are of uniform quality.

The sample is weighed, and 10 to 20 grams are placed in a small beaker, which is heated over a hot plate to drive out any moisture that may be present in the oil. The sample is allowed to cool and is then diluted with naphtha in the proportion of 10 parts of oil to 90 parts of naphtha. The oil goes into solution with the naphtha, but the sludge and solid materials drop out. The insoluble materials are removed in a special type of apparatus known as a Gooch filter, wherein the residue is retained by an asbestos mat, washed clear with naphtha, then dried. The increase in weight of the Gooch filter is the weight of the insoluble materials, and this weight is reported as "per cent insoluble in naphtha."

To separate the oxidized oil from the solid material, the residue is next washed with hot benzol. When all traces of oxidized oil have been dissolved and eliminated, the remaining material is again weighed and reported as "per cent insoluble in benzol."

The decrease in weight after washing with benzol is of course the weight of oxidized oil. This weight is easily expressed as a percentage of the original sample. The permissible percentage of oxidized oil in a lubricating system varies with the equipment and service conditions.

The materials insoluble in benzol may be composed of soot, worn metal particles, rust, and various impurities. It is most difficult to set a maximum safe limit for benzol insolubles, as the nature of the material has much to do with the extent of damage that may result. Metal particles or abrasive materials may generally be considered detrimental. A far larger quantity of soft nonabrasive material may be tolerated.

The following insolubility tests were carried out on a sample of used oil withdrawn from the crankcase of a large Diesel ship:

Operating hours	430
S.A.E. number	30
Per cent insoluble in naphtha	0.28
Per cent insoluble in benzol	0.24

The oxidized oil content was 0.28 minus 0.24, or 0.04 per cent. The per cent insoluble in benzol was found to be carbonaceous matter (probably soot) with a trace of iron oxide. The oil as represented by the complete analysis was considered to be in good condition and suitable for continued service.

Per Cent Insoluble in Petroleum Ether, Per Cent Insoluble in Chloroform

This test is carried out in the same manner as the previous test, and the results are similar, ether taking the place of naphtha and chloroform taking the place of benzol.

Ash Test (Per Cent Ash)

As the name implies, this test is carried out by burning all the combustible products (from a sample of 20 grams), and the test may be specified for new or used oils. When straight mineral oils are new they register no appreciable ash content. Gear oils containing compounds of lead, detergent oils, etc., will show an ash content, owing to the metallic compounds used. Heavy residual products may contain ash in varying amounts.

In practice the sample is heated in an open crucible until it becomes cherry red and the oil can be ignited. The burner is then removed and the oil allowed to burn completely. The residue is then placed in a muffle furnace until all carbon and carbonaceous matter is burned and only noninflammable material remains. In specifications covering new oil the limit of allowable ash content is generally included to guarantee against any excess amount of detrimental impurities which might be present to cause wear.

The per cent of ash found in a used oil is extremely useful in determining materials that may be present to cause wear. For example, the test is carried out on used oil samples withdrawn from the crankcases of internal-combustion engines and from many other applications where injurious hard materials may be present, as, for example, samples withdrawn from gear cases. The percentage of ash in a used oil is an index of potential wear. For straight mineral oils an ash content of 0.10 per cent is generally considered to be a maximum safe limit in any sample taken from the crankcase of an internal-combustion engine. In other applications where this test may be carried out on a used oil, 0.05 per cent is generally considered to be a maximum limit.

Ash content may be further analyzed at great length, depending upon the subject and necessary amount of research work required to identify the materials.

A simple analysis would be that of a used motor oil, wherein siliceous material from atmospheric dust would be reduced by hydrochloric acid, iron oxide would be extracted, and so forth. However, this is not the general procedure for the reason that a percentage ash content of possibly 0.10 for straight mineral oils would be sufficient reason to change or filter the oil. This percentage would be considered high in many engines. For example, if the sample from a reduction gear unit tested 0.10% ash, the contents would likely consist of metallic oxides and worn metal particles. An examination of the gear teeth would be warranted. This test does not disclose lint, paper dust, and other organic impurities, as these materials are combustible.

Interpretation of Analyses of Deposits in Oiling Systems

The percentage of oil extracted by naphtha indicates how much of the apparent sludge is good oil.

The percentage of oxidized oil extracted by benzol indicates to what extent the oil has broken down.

The difference between the ash content and the benzol insoluble represents the organic compounds, such as carbon and lint.

The percentage of water is a value which may explain oil breakdown. Presence of considerable moisture will not only cause oil to oxidize, but it may form an emulsion having the appearance of a soft sludge.

The percentage of ash represents incombustible materials. It may include abrasive materials, such as dust from the air (silica), iron particles from the equipment (iron oxide), metallic particles from wear, and other oxides which represent wear of the numerous metals present in mechanical equipment.

By means of the analysis, the chemist can often determine whether the sludge was caused by poor oil stability, poor mechanical condition of the equipment, or contamination from outside sources. To reach a conclusion it is necessary to consider service conditions, length of operation, and the actual quantity of sludge which has been formed.

Methods of sludge analysis and interpretation of results differ considerably in view of the complexity of this whole subject, and various methods are employed by different laboratories. Whenever samples of sludge or residue are submitted to a petroleum chemist it is important that all pertinent data connected with the operation of the equipment be carefully outlined.

11

Functional Tests

Functional tests are designed to evaluate some of the desired service characteristics of a lubricant. The tests are usually accelerated in order to obtain useful information in a short period of time, and are therefore not truly representative of service conditions. Thus the test results must be analyzed very carefully in order to apply them intelligently. As an example, the rusting test provides information as to an oil's tendency to minimize rusting in the presence of modest amounts of moisture but is meaningless if large volumes of water are present.

In this respect these tests differ from the physical tests described in the previous chapter. Many physical tests give very little, if any, indication of the performance that a lubricant may give in service, and are used mainly for control purposes.

Rust Test

This test is primarily intended to indicate the ability of new steam turbine oils to prevent rusting in the event that water enters the charge. However, the test is useful when applied to any new oil that may be placed in continuous contact with iron or steel and mixed with water. For example, gear housings tend to accumulate small amounts of water from condensation, and the effect sometimes accelerates rusting. The same is true for hydraulic systems using oil as a fluid medium.

Owing to their high surface tension, many new and highly refined mineral oils lack the ability to wet metals. Consequently, if any moisture enters or condenses in the oil system, the oil may be displaced by the moisture and rusting will result. To overcome this condition, particularly in new installations, a small quantity of mild acidic material is sometimes added to promote better oil-coating qualities.

The test procedure is carried out by first immersing a polished steel specimen in 300 milliliters of the oil to be tested and stirring for 30 minutes to coat the specimen, then adding 30 milliliters of distilled water.

The contents in the beaker do not mix, but the oil and water is agitated and stirred for 24 hours. In the meantime the temperature is maintained at 140° F.

At the end of the test, the rust on the steel specimen is reported as none, light, moderate, or severe, depending upon whether there are no rust spots, only a few rust spots, about half the surface is coated with rust, or approximately all of the surface is coated with rust.

This particular test is carried out under prescribed conditions as to size of steel specimen, etc., and the temperature is maintained at 140° F to approximate the conditions which prevail in the circulating oiling systems of steam turbines. However, with time and service, all mineral oils oxidize and develop their own fatty acids, which are protective. Hence, the test is of particular interest when the oil is to be used in new equipment wherein the parts have not been touched with oil, and might therefore be vulnerable to rusting if moisture should be present, or should gain entrance, before the new oil has had time to accumulate sufficient fatty acids to provide protection. This test is also used to determine the effectiveness of additives to prevent rusting in both new and used oils. In order to eliminate this hazard in new turbine installations, the refiner is generally charged with the responsibility of supplying an oil that will pass this test.

The rusting test as outlined is a dynamic test. If in service the oil system remains static and condensation of water occurs, rusting above the oil level could occur even though the oil had passed the rust test. There is no standard test to determine rusting under static conditions. When rusting occurs in a system containing an oil that passes the rust test, one should look to the mechanical and operating practices in order to reduce the water in the system. The advent of oils containing additives to minimize rusting has reduced rusting from a frequent to an infrequent occurrence.

Bearing Corrosion Tests

Several laboratory and full-scale engine tests have been developed to gage and measure the corrosive effect of used or aging lubricating oils on different types of metals. As a rule this type of test is carried out by maintaining the oil at a fairly high temperature, as, for example, 300° F, and circulating it around the metal or metals which will come in contact with the oil during its service life.

These tests are sometimes stipulated in specifications, and then the apparatus and conditions are outlined. The purpose is to record the condition of the metal specimens and measure the loss in weight of the specimens after the oil has been circulated for a prescribed number of hours. Because all mineral oils eventually succumb to the process of oxidation and develop organic acids, this type of test is a guide to the possible corrosive action which may be anticipated on various bearing metals when the accelerating action of heat is present to form these acids more rapidly.

Since lubricating oils vary greatly in their molecular construction, they naturally show different results in corrosive activity. These tests are also instructive in determining the effect of additional compounds, such as oxidation inhibitors and carbon-dispersing agents.

Babbitt metal is practically immune to any reaction with petroleum acids, but some of the newer and harder bearing metals, such as the lead coppers, are particularly susceptible to the organic acids formed during the oxidation of an oil. Cadmium silver and some other alloys composed of metals far apart in the electrochemical series are affected by galvanic corrosion at elevated temperatures. This type of test is primarily adopted to investigate the effectiveness of internal-combustion-engine oils in preventing bearing corrosion. It is therefore apparent that the bearing materials must be taken into account when specifying lubricants.

Engine Tests

There are no laboratory tests that duplicate the service conditions of an oil in an internal-combustion engine. Operating conditions, fuels, design, etc., all affect engine and oil performance. The Coordinating Research Council, sponsored by the American Petroleum Institute (A.P.I.) and the Society of Automobile Engineers (S.A.E.), has developed a series of engine tests designed to determine essential characteristics of crankcase oils. The test conditions are very closely controlled, and the tests are time consuming and costly. However, these tests have proved reliable and are an excellent means of screening crankcase oils. The tests are relative in that it is doubtful if small differences can be evaluated. Also, most oils are better than others in certain respects, so that it is very difficult to differentiate between any two oils when both have a high rating. For instance, one oil might show very good ring conditions at the expense of some bearing weight loss, while another oil might show no bearing weight loss at some expense to ring deposits. Test conditions for some engine tests are shown in the table.

	Type of Engine Test			
	L-4	*L-1*	*L-3*	*L-5*
Time, hours	36	480	120	500
Fuel	Gasoline	Diesel	Diesel	Diesel
Engine speed, rpm	3150 ± 25	1000 ± 10	1400 ± 14	2000 ± 20
Engine load			37	3 cyl. 78 ± 2
Brake horsepower	30	2950 Btu		4 cyl. 103 ± 3
Jacket temperature		20 approx.		
Outlet, °F	200 ± 2	175/180		
Inlet, °F	190 min.	160/165	200 ± 2	180 ± 3
Oil sump temperature				
S.A.E. 30–50	280 ± 2			
S.A.E. 10–10W	265 ± 2			230 ± 2
Oil temperature to bearings		145/150	212 ± 2	
Oil change, hours	None	120	None	None
Air-fuel ratio	14.5 to 1 ± 0.5			
Cylinders	6	1	4	3 or 4
Bore, inches	3.5	5.75		4.25
Stroke, inches	3.75	8		5.0
Intake air temperature			140 ± 5	
Cycle	4	4	4	2

L-4 Engine Test

This test is designed to determine the oxidation stability and bearing corrosion properties of a crankcase oil under heavy-duty conditions, and it does not evaluate ring sticking or combustion chamber deposits. The test is equivalent to a speed of 60 miles per hour during severely hot weather. Varnish and sludge deposits are rated from 0 to 10 for various parts of the engine. A rating of 40 for varnish and 40 for sludge, giving a total rating of 80, has been found to give suitable performance under heavy-duty conditions. A crankcase oil with a total rating much less than 65 can be considered relatively poor. Corrosion of copper-lead bearings is determined by weighing each connecting rod bearing insert at the beginning of the test. A weight loss at the end of the test of less than 0.30 grams per insert may be considered good. A weight loss of 0.30 to 0.60 is borderline, and corrosive oils may well run over 0.60 grams. At the conclusion of the test the oil is usually tested for resins, viscosity change, acids, etc.

L-1 Engine Test

This test determines the effect of an oil on ring sticking, lacquering of pistons, wear and accumulations of deposits, and scuffing of the crown of the piston. Some of the means of evaluating the test are carbon deposits, wear of the cylinder, number of stuck or tight piston rings, etc. An appreciable amount of any of these factors would rate an oil as unsatisfactory. This test is designed for evaluating heavy-duty motor oils that contain detergents.

L-3 Engine Test

For the most part this test evaluates the same things as the L-1 test, with the addition of measuring the corrosion of copper-lead bearings.

L-5 Engine Test

This test is the most severe of the engine tests, and heavy-duty motor oils must contain both an oxidation inhibitor and a detergent in order to pass the test satisfactorily.

Lauson Engine Test

This is a single-cylinder, relatively inexpensive engine test used in developing crankcase oils. Oils which pass this test may warrant a full-scale engine test. The engine and test conditions have not been standardized, but are usually run from 60 to 100 hours at 1800 rpm, with a load of 2 horsepower and with oil temperatures of 170° to 300° F. This range provides a means for measuring bearing corrosion, ring sticking, and oil stability. In addition to these tests it is common practice to observe engines in service to determine the oil's performance.

Oxidation Test

Oxidation is a normal process that occurs at all temperatures. At low temperatures the rate of oxidation may be so low that it is not measured or recognized. The rate of oxidation doubles for about each 15° rise in temperature. The process of oxidation is important when equipment is operated above 130°, and becomes of major importance when temperatures are above 150°. Various metals and other materials act as a catalyst and accelerate the rate of oxidation. The addition of oil to a system retards oxidation. The following table illustrates the effect of temperature, and also points out the short test life of an oil at elevated temperatures. All oxidation inhibitors have temperature limitations. If the oxidation test is run at a higher temperature than the oil in service, one can expect a much longer life from the oil. It is dangerous to accept any oxidation test results if an oil will be at a higher temperature in service. These facts make it difficult to develop a quick test, as heat is necessary to accelerate a test, and yet, if we accelerate the test too much, we have extreme difficulty in interpreting the results in terms of service at a lower temperature.

Temperature in Degrees Fahrenheit	*Oxidation Life in Hours*
300	50 (2 days)
285	100
260	200
245	400
230	800
215	1,600
200	3,200
185	6,400
170	12,800
155	25,600
140	51,200 (6 years)

The Funk, Indiana, and Sligh oxidation tests were developed for straight mineral oils and are not reliable for testing additive-type oils.

Funk Sludge Test

There are several oxidation tests, but all are based on creating artificial conditions that will oxidize the oil and cause sludge to form in measurable quantities.

The Funk sludge test is an example of a well-known test devised to emulate the worst possible conditions occurring in turbine oiling systems. In this test, 8 gallons of oil are used, and all the factors which cause sludge to form are exaggerated to give reasonably fast readings of sludge production. The Funk tank contains copper baffle plates to provide the catalytic effect that might occur as a result of contact with this particular metal or its alloys; air is mixed intimately with the oil to represent the effect of contact with air in actual service; the temperature is maintained at 210° F to hasten the process of oxidation; and 0.8 gallon of water is added to represent gland leakage.

Each hour in the Funk machine is assumed to represent about 100 hours of actual service in a turbine oiling system. Samples are taken at 5-hour intervals and centrifuged to measure the sludge content. When 1 per cent of the charge has been converted to sludge the resistance is measured by the number of hours taken to produce this 1 per cent of sludge.

Indiana Oxidation Test

This tests the resistance of an oil to sludging. In a general way the test gives some idea of the sludging characteristics that may be anticipated in service when the oil is subjected to high temperatures.

As soon as a small amount of sludge has formed in any oil, the rate of formation generally increases more rapidly thereafter, and, since sludging tests are carried out by accelerating the rate of oxidation, the test is artificial and not particularly reliable as a blanket comparison between different grades.

The Indiana oxidation test is carried out by heating 300 cc of the sample to 341° F in glass and bubbling air through at a rate of 10 liters per hour. To find the amount of sludge present in a given time, a 10-gram sample of the oil is diluted with 100 cc of specified naphtha, and, since only the oil goes into solution, the sludge or oxidized oil drops out and remains in a filter. The amount of sludge is reported in milligrams per 10 grams of oil.

In general, lubricating oils of low A.P.I. gravity tend to sludge more rapidly than oils of comparable viscosity but higher gravity. The following table is representative for a few samples of motor oils of various grades when subjected to the Indiana test.

S.A.E. No.	*Viscosity Index*	*10-mg Point in Hours*	*100-mg Point in Hours*	*Per Cent Increase in Viscosity after 100 Hours*
30	10	20	50	100
30	55	10	30	80
30	100	90	130	40
30	105	100	135	50
30	110	[1]	[1]	100
50	102	[1]	[1]	80

[1] Less than 10 milligrams of sludge per 10 grams of oil after 100 hours.

Sligh Number

The Sligh test is an oxidation test wherein sludging characteristics are determined by heating the oil in the presence of oxygen. In this test 10 grams of oil are placed in a glass flask and heated in the presence of 90 cc of oxygen for 2½ hours at a temperature of 200° C. Upon completion of this reaction period, the sample is diluted to 100 cc by adding a specified grade of petroleum naphtha. The solution is then allowed to stand for 1 hour at a temperature of 25° C.

Lubricating oils are soluble in naphtha, but oxidized oil or sludge is insoluble and therefore drops out of the solution. The oil-naphtha solution is filtered through a suitable medium, and the sludge is separated and weighed. The Sligh number is the number of milligrams of sludge per 10 grams of oil. The following readings are representative for Pennsylvania motor oils, which run low in Sligh number.

S.A.E. No.	*Viscosity Index*	*Sligh No.*
20	100	2.7
30	100	2.5
40	100	1.5
50	100	1.0

Pennsylvania oils have very low Sligh numbers. Mid-Continent grades run just a little higher. Depending upon the type of crude, blend, refining methods employed, viscosity, etc., the Sligh number may range from 0 to 100.

A.S.T.M. Tentative Test for Oxidation Characteristics of Steam Turbine Oils

This is a test for determining the oxidation-inhibitor life in a steam turbine oil. As such, it aids in determining the resistance of the oil to oxidation. The test may be run for 1000 hours; at this time the acid number should be less than 2.0. Sometimes the test is stopped when the acid number is only 0.25, since, when a significant change in the acid number occurs, it may be said that the inhibitor has begun to lose its effectiveness. Test results and their interpretation will be discussed further in Chapter 21, "Steam Turbines." Figure 1 shows the test cell. Oil and water are placed in the test cell together with copper and iron wire to act as a catalyst. Oxygen is introduced into the cell, which is maintained at a temperature of 203° F. Oils passing this test have excellent records in steam turbines. Even though the iron catalyst may show severe rusting, the rusting does not occur in service below the oil level. It is believed that the excess of water in the test is unrealistic and does not represent the water that may be in a turbine even under adverse service conditions. This test may be applied to all circulating and splash systems using turbine oils as a lubricant.

Octane Number

Measurement of the antiknock qualities in a particular grade of gasoline is determined in a special gasoline engine built to specifications. This is a single-cylinder engine equipped with a movable cylinder head which allows variations to be made in the compression ratio within the cylinder, and the design is known as a C.F.R. engine (Commercial Fuels Research Committee).

In this test isoöctane is given an arbitrary rating of 100 on account of its high antiknock value, while normal heptane, which is about the worst knocking fuel known, is given a rating of 0. Normal heptane employed for reference purposes is obtained by distillation and purification of the sap from a species of pine tree that grows in California.

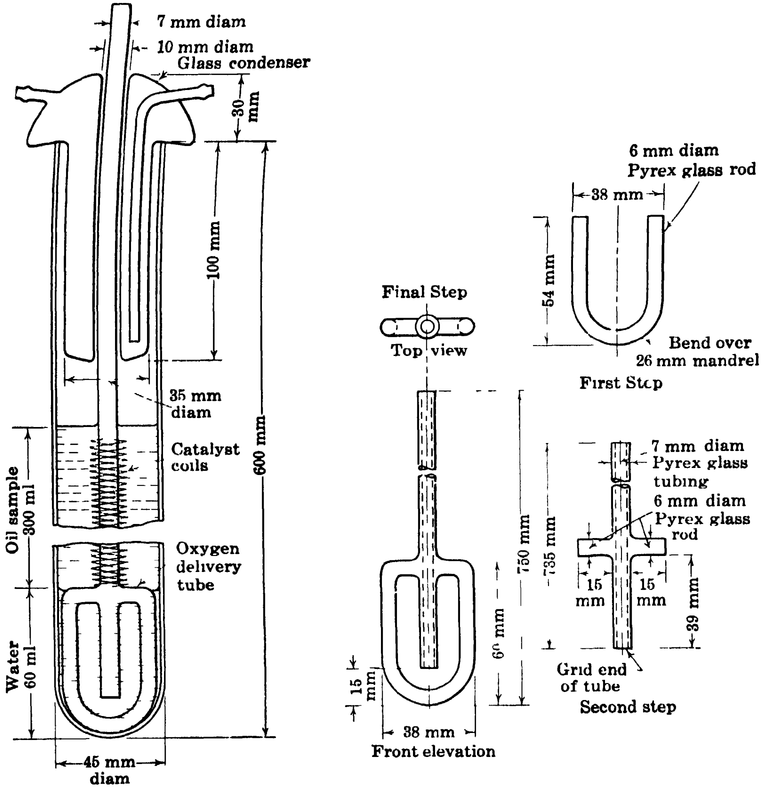


Fig. 1.

This type of hydrocarbon is also found in straight-run gasoline. Fortunately, the percentage is small. Isoöctane is made from cracked petroleum and processed by synthetic methods. Both reference fuels are colorless, uniform, and stable, and both have similar physical properties. The difference in knock performance is due to a difference in the atomic arrangement of the molecules, a feature which remains unexplained. During the test three fuels are placed in separate tanks, as shown in Fig. 2. The C.F.R. engine is run on the gasoline of unknown antiknock property and the compression ratio gradually increased by moving the adjustable cylinder head until knocking is registered. At this point the gasoline is shut off and a mixture of isoöctane and normal heptane is supplied to the C.F.R. engine. This mixture is adjusted until it just matches the knocking point registered by the gasoline. Assuming that the match was composed of 75 per cent isoöctane and 25 per cent heptane, the gasoline under test would be given a commercial rating of 75 octane.

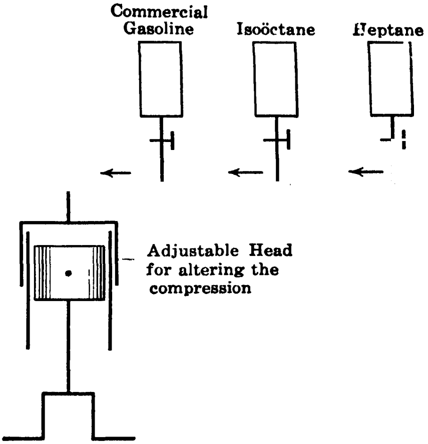


Fig. 2.

The dimensions of all parts of the C.F.R. engine are calibrated to specification, and, in addition to the adjustable cylinder head, there are of course sensitive knock-recording instruments and similar details common to laboratory testing engines.

The term "octane number" has nothing to do with the actual composition of gasoline but is entirely an arbitrary measurement of the antiknock property. With the introduction of improved methods of manufacturing synthetic fuels of high antiknock value it is possible to produce gasoline engine fuels which have much higher antiknock values than 100 as compared with isoöctane.

Straight-run gasolines have octane ratings of about 45 to 60, cracked gasolines 75 to 90, and of course blends of these two grades have intermediate octane numbers. The addition of 1 cc of tetraethyl lead to a gallon of gasoline will raise the octane number approximately 10 points. This factor varies with different types, but no more than 4 cc per gallon are allowed by law on account of its poisonous nature. Curiously enough, most grades of gasoline become saturated with the addition of 5 to 7 cc of tetraethyl lead, and amounts above this will not raise the octane number higher; about 20 points is the limit.

Cetane Number

This test measures the knock characteristics of a Diesel fuel. The method rates the fuel in an actual engine known as the C.F.R. Diesel fuel-testing engine. This is a single-cylinder Diesel engine manufactured to specifications outlined by the Commercial Fuels Research Committee. In this test two reference fuels are used: cetane, which has excellent ignition qualities when used as a Diesel fuel, and alpha-methylnaphthalene, which has a long ignition delay.

The engine is run on the fuel to be tested, and knock characteristics are recorded by instruments. Upon completion of this test, the fuel is shut off. Next, a mixture of cetane and alpha-methylnaphthalene is employed as a fuel and the proportions adjusted until the mixture just matches the knocking characteristics recorded by the fuel under test. For example, if a mixture of 56 per cent cetane and 44 per cent alpha-methylnaphthalene produced the same knocking characteristics as the fuel under test, then the particular fuel would be given a cetane number of 56.

A variation of this method, also using the C.F.R. engine, is the critical compression ratio (C.C.R.). The procedure for this test involves a determination of the lowest compression ratio at which the fuel will fire. Blends of the same standard fuels as used in the delay method are then made up until one is found having the same lowest-compression ratio as the sample being tested, and the per cent cetane in the blend is reported as cetane number (C.C.R.). This method is not as popular as the delay method, since it indicates starting rather than running quality.

Diesel Index

Diesel index is a method which entirely depends on the physical characteristics of the fuel. It is calculated by measuring the A.P.I. gravity and the aniline point and using the following formula:

$$\text{Diesel index} = \frac{\text{A.P.I. gravity} \times \text{aniline point (°F)}}{100}$$

The A.P.I. gravity is measured by means of a hydrometer in the usual manner.

The aniline point is the lowest temperature at which equal parts by volume of freshly distilled aniline and the test sample of oil are completely miscible. It is determined by heating the mixture in a jacketed test tube to a clear solution and recording the temperature at which turbidity appears as the mixture cools. The test is indicative of the percentage of paraffinic molecules in the fuel, and is of value because fuels distilled from paraffin-base crudes give best results from an ignition standpoint. While cetane number (delay) and Diesel index are based on entirely different approaches to the problem, the following table, which is the result of actual experiments with a variety of No. 2 straight-run distillate fuels, shows that there is some correlation. The samples vary from the Gulf Coast to the Pennsylvania fields.

DIESEL INDEX AND CETANE NUMBER (DELAY METHOD)

Diesel Index	*Cetane No.*	
10	26	Gulf Coast
20	31	
30	36	
40	42	Mid-Continent
50	48	
60	55	
70	63	Pennsylvania
80	73	
90	83	

Many other methods for rating Diesel fuels have been suggested, but the two foregoing are the most popular. This is probably because one is an actual test in an engine, while the other is a very simple calculation which shows some relationship to service results.

Load-Carrying Tests

The load-carrying capacity of a lubricant is the maximum load which can be imposed upon a given system containing the lubricant and operating under specific conditions without permitting film failure that would result in seizure, welding, galling, scoring, or excessive wear of the surfaces. This property is often referred to as "film strength."

Several laboratory machines have been devised to determine the maximum load-carrying capacity of oil films when operating under prescribed conditions of load, speed, and temperature. In order to secure a flood of oil to the test pieces they are generally submerged in a bath of the oil to be tested. Since the test pieces are scored after each experiment, they are of necessity miniature in size and are generally purchased by the thousand to secure a uniform batch. This procedure gives reasonable certainty that the metal and machining of each piece will be similar, thus assuring comparable test results.

Figure 3 shows the operating principles of a testing machine. *A* is the revolving test shaft, *B* the test bearing, and *C* the oil bath. The pressure on the bearing is increased by adding weights to the end of a lever, which is supported by a knife edge on top of the bearing. When rupture of the oil film occurs, metal-to-metal contact takes place and the resulting noise is easily recognized. This particular type of test, with recording instruments and other refinements, is sometimes carried out on full-size railroad car journals and other actual bearings and gears, etc., to test the load-carrying ability of lubricants, effect of oil temperature, etc.

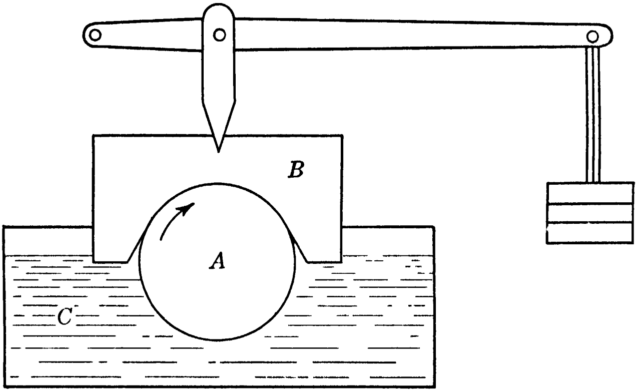


FIG. 3. Diagrammatic sketch showing principle employed for testing oil-film strength under stipulated conditions.

The following is a partial list of laboratory testing machines employed to determine the relative load-carrying ability of lubricants:

Actual models (bearings, gears, roller bearings, etc.).
S.A.E. machine (Society of Automotive Engineers).
National Bureau of Standards machine.
Timken machine.
General Motors machine.
Almen machine.
Four ball machine.
Falex machine.

These different machines give some data, but they do not correlate. In other words, an oil that carries the highest load on one machine may carry a low load on another machine. However, this type of test is extremely useful in determining the comparative load-carrying abilities of different types of lubricants.

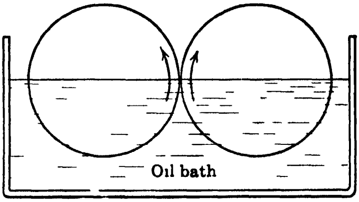


Fig. 4.

These machines do not show significant differences between straight mineral oils. They are designed to study the antigalling, seizure, and wear properties. In order to do this, the test must be designed to break through any lubricating oil film so that mating surfaces come into contact. Occasionally these machines are used as a spectacular demonstration to the uninformed public in order to sell products for service conditions which do not require the properties that the machines test for.

Very often a test is included in specifications covering the purchase of compounded lubricants for gear service, in which case the name of the testing machine and minimum test results are stipulated. For example, if the lubricant is to be used for hypoid gear service the specification might require that the lubricant have a load-carrying capacity of not less than a specified number of pounds when tested on a certain machine. Figures 4, 5, and 6 show the operating principles of some of the test machines. Some full-scale specific-purpose test machines have been developed, such as the "Gleason," for testing hypoid gear lubricants, and full-scale automobile differential and transmission tests.

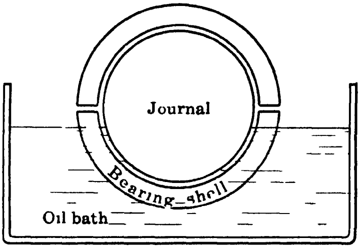


Fig. 5.

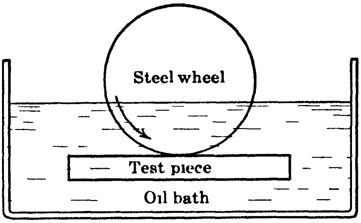


Fig. 6

12

Greases

Lubricating greases are usually soap-thickened mineral oils to which the different soaps employed as thickeners give a variety of textures. The soaps are polar compounds and have a high affinity for metal. A calcium soap will give a buttery texture, and a sodium soap a fibrous structure, when mixed with the same oil. Many thickening agents are being added to both petroleum oils and synthetic oils to make grease. Some of the more common thickening agents are bentonite and silica gel, and ucons and silicones are among the synthetic oils.

Differences in physical properties and appearance are important factors in determining the suitability of the lubricant for a particular requirement. For instance, the spongy texture, which denotes a high degree of internal cohesion within the grease body, is more effective than the shorter-shear, buttery texture in resisting centrifugal force and channeling. Therefore it is more suitable for ball, roller bearing, and gear lubrication. On the other hand, the short-shear, low-cohesion lubricants flow easily and are more serviceable for plain sleeve bearings.

Greases of soft consistency have become of major importance. The hard soap-oil mixtures previously used have given way to lighter-bodied lubricants with superior lubricating qualities. Changes in mechanical construction, the increased speed of machine parts, and changes in the means of applying greases have introduced a need for this type of lubricant.

When selecting grease for a particular industrial purpose choose the grade that contains a lubricating oil adapted to the operating conditions. For example, if a general-purpose grease is required in a gun, the oil in the grease should be about S.A.E. 20. This would be about the viscosity of a general-purpose lubricating oil.

The grade and viscosity of the mineral oil used is largely responsible for the lubricating value of a soap-oil mixture; and the higher the speed, the lighter should be the oil in the grease. Conversely, the lower the speed, the heavier the oil. This is a fundamental rule in lubrication. However, grease-lubricated mechanisms are not as sensitive to the oil

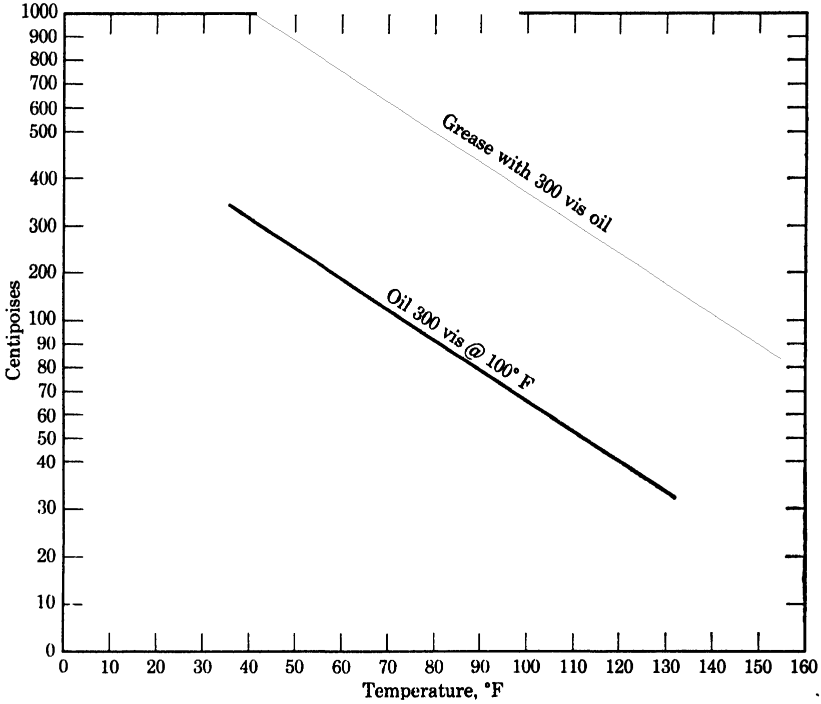


Fig. 1.

used as if oil were used alone. An examination of Fig. 1 shows that the viscosity change of a grease caused by temperature parallels the viscosity change of the oil used in making the grease. It will be noted that the grease has a higher viscosity than the oil at any temperature.

Greases in general, regardless of texture or consistency, may be classified roughly into the following five groups:

1. Admixtures of mineral oil and solid materials.
2. Heavy residual oils of the asphaltic type, used straight or blended with lighter lubricating oil fractions such as steam cylinder stocks.

3. Soap-thickened mineral oils.
4. Extreme-pressure greases.
5. Roll-neck greases.

Lubricants in groups 1 and 2 are in one sense of the word "specialty" products, because they have a limited range in the lubricating field. They are known by such trade names as Tractor Roller Greases (used to lubricate track chain bearings on tractors), Wire Rope Compounds, and Rock Bit Lubricants (used in connection with oil well drilling).

The greases in the first group are generally composed of mineral oils and soap compounded or mixed with "solid lubricants," such as graphite, mica, talc, and asbestos fibers. They are used for the lubrication of rough-fitting machine parts functioning under heavy loads at slow speed. The filler or solid lubricant absorbs the force of impact, preventing severe metal-to-metal contact. Furthermore, in functioning as a filler, the solid lubricant tends to smooth away any roughness which may be encountered. This indicates that the fillers are mild lapping compounds. Under sustained high load this permits a uniform low rate of wear. Under intermittent high loads or very low speeds the wear rate is negligible and can be tolerated.

Examples of group 1 are lubricants for tractor rollers, unloading devices, concrete mixers, and mechanical digging equipment.

The second group, consisting of heavy asphaltic mineral oils and blends of lighter petroleum fractions, are especially suitable for wire ropes, and gears of the open type. Asphaltic residue, often called still bottoms, is highest in favor as a base because its high specific gravity and high degree of metallic adhesion make it less likely to be thrown off when used on open gears or of oozing out when used on wire ropes and cables.

While not a grease in the general sense of the word, this type of lubricant is made either by distilling the crude to the desired consistency or by blending a heavy residuum with a lighter petroleum fraction. In some instances, such as with wire rope compounds and lubricants for open-type gears, it is common practice to thin the heavy mineral oil with a light volatile naphtha. The volatile portion subsequently evaporates upon exposure on the machine part, leaving a tenacious lubricant. However, the better practice is to use these lubricants in a viscous or semisolid state and to apply heat before painting gear teeth or coating wire ropes and cables. Upon cooling, this type of lubricant regains its former body and tacky properties.

Soap-Thickened Mineral Oils

The discussion of the third group, the soap-thickened mineral-oil type of greases, will cover generally the manufacturing procedure, physical properties, and the relation of physical properties to lubricating service. Soap-oil mixtures are the most commonly known greases.

They are used in place of mineral oils when difficulty is encountered in applying oil. By reason of heavier body and greater resistance to flow, they are less wasteful, and a soap-oil product will lubricate for a comparatively long period of time without attention or replenishment.

The soaps commonly employed as thickeners include sodium, calcium, aluminum, barium, lithium, and strontium. Lead soap has little thickening effect. This property makes it a desirable additive for gear lubricants. The soaps are the products of chemical reaction of a fat (animal, vegetable, or synthetic fatty acid), and metal bases. The metallic base determines the type of soap and plays the major part in forming the general physical properties of the finished grease.

Calcium Soap Greases

Calcium or lime soap greases are probably more in demand than any other soap-thickened lubricant. The commonly known varieties include the several grades of cup grease, pressure gun grease, axle grease, and water pump grease. The greases, ranging from semifluid to semisolid consistency, contain from 4 to 25 per cent of soap. The mineral oil content is usually a highly refined grade having a viscosity rating from 100 to 1000 S.S.U. at 100° F, depending upon the service.

Lime-base products may be made in two ways and are classified, according to the method used, as cold-set greases and hot-mixed greases.

The cold-set greases are made by mixing rosin oil, lime, and mineral oil. Saponification takes place and the mixture hardens without application of heat from an outside source. Rapid saponification, cold, is peculiar to the fatty members predominating in rosin oils.

Cold-set greases are comparatively inexpensive and are designed for rough duty; they are extensively used on agricultural machinery, where they are known as axle greases, and on oil-field pumping equipment, where they are known as jack post greases.

Hot-mixed lime soap greases are made by saponifying tho fatty ingredient with an accurately measured amount of hydrated lime. The chemical reaction is carried to completion in either open-type steam-jacketed kettles or closed-type pressure cookers. The great majority of cup, pressure gun, and water pump greases are manufactured by this method. The soap may be likened to a sponge which absorbs the oil.

Lime soap greases are not applicable where the temperature is apt to rise above 160° F. The grease is not a true solution of soap and oil; it is a suspension of soap and water in oil and is dependent upon a small percentage of water content to maintain the grease body. This water content is generally about 0.5 to 2 per cent. Consequently, at a temperature in excess of 160° F the grease gradually loses its moisture, and separation of soap and oil results. The advantages of lime soap grease are insolubility in water and a buttery texture. The grease is easily displaced by centrifugal force, which permits it to channel readily, making it unsatisfactory for high-speed ball bearings.

Lime soap greases are also made with special ingredients to raise the melting point possibly as high as 400° F. Such products as lead soap may be employed to replace most if not all the water.

The calcium soap greases separate into oil and soap rather easily under pressure, high temperature, and excess of water. Where water is encountered rusting is likely to occur when equipment is idle, as the water seems to displace grease from the surface of the metal. If the equipment is greased often enough to exclude the water, the calcium soap greases may be used successfully.

Sodium Soap Greases

The equipment and manufacturing procedure for sodium- or caustic soda-base greases are essentially the same as those used for lime-base greases.

However, soda soap greases have a characteristic sponge or fiber-like texture and possess a high degree of cohesion within the grease body. The light-bodied grades are extensively used for ball and roller bearings and occasionally for gears.

Soda soap greases have high liquefaction temperatures, generally 300° to 350° F. Consequently, this type of grease is used on machine parts which operate in proximity to heat. The more commonly known grades of soda base greases are automotive wheel bearing, universal joint, and steering sector lubricants.

These greases readily form emulsions with water. As long as the emulsion can be retained in the bearing it will afford lubrication and protect the parts from rusting. However, soda soap greases require only a trace of water content to form a bond, and the best grades will not separate under temperature. When melted by heat they will regain their former characteristics upon cooling.

Ball and roller bearing greases of soft consistency generally contain a combination base of lime soap and soda soap.

Sodium soap greases are very often manufactured with viscous oils, such as cylinder stocks, because they are so often used for high-temperature applications. In addition to having a melting point of about 350° F, the heavy oil adds to the lubricating value at elevated temperatures.

Aluminum Soap Greases

Aluminum soap greases compare closely in texture and lubricating qualities with calcium soap greases. However, they have a more brilliant transparent appearance and are more stable. Every ingredient plays an important part in shaping the physical properties of the resultant product. The aluminum soap of stearic acid, incorporated with low-viscosity mineral oil, yields a grease product of low cohesive character, as evidenced by its buttery texture. The aluminum soap of oleic acid, incorporated with the same mineral oil, yields a product of extremely high cohesive character and pronounced rubbery texture.

Contrasted with other soaps herein discussed, aluminum stearate, when incorporated with an oil of extremely high viscosity, yields a grease of softer consistency than when incorporated with a mineral oil of low viscosity. The rate of cooling also has an important bearing on the grease texture and consistency.

It is necessary for the grease manufacturer to make an extensive study of the mineral oil, the fatty ingredient, and also the cooling rate best suited for the grade he wishes to manufacture.

The manufacturing procedure for aluminum soap is different from that for other soaps. This soap is a product of chemical substitution. The fat is first saponified with caustic soda. Then by the addition of an aqueous solution of an aluminum salt the sodium radical of the soap is replaced by aluminum. The water-insoluble aluminum soap separates, thus permitting the sodium salts to be drawn off. By repeated washings, the aluminum soap is freed entirely of excess saponifying agents.

This type of grease is very adhesive to metal surfaces. This property provides rust protection in the presence of water but makes the grease unsuitable for high-speed application because of the excessive internal friction of the grease.

The grease is very stable, resists separation, and leaves a minimum of soap deposits, and therefore finds applications in slow-speed bearings.

At temperatures much above its melting point, 200° F, its physical characteristics are drastically changed, so that the grease resembles rubber.

Barium Soap Greases

Barium soap greases have a wide range of operating temperature limits and may be classified as multipurpose greases. They have melting points similar to the sodium greases, and resemble the aluminum soaps in water resistance. The barium greases are used principally in mining and construction equipment.

Lithium Soap Greases

Lithium greases are generally manufactured with low-pour point oils, because this type of soap will hold very light oils with little separation, and therefore is useful for low-temperature applications. This grease has been used for temperatures as low as −60° F. It has a high melting point when manufactured with higher-viscosity oils. It must be kept in mind that the same lithium soap grease cannot be used at very low temperatures and very high temperatures. The lithium greases are water resistant and have good metal wetting properties, which makes them multipurpose greases.

Lead Soap Greases

Products containing lead soap are classified as grease, even though most of them are fluids. Many gear oils contain lead soap because of its mild E.P. properties. There are two types of lead soap: lead oleate and lead naphthenate. It is very difficult mechanically to remove the lead naphthenate from the oil. The lubricants are used for bearings and gears under severe operating loads.

Plug Cock Greases

Plug cock greases function as a seal between the plug and valve body. They must have sufficient lubricating value so that the valve can be operated without straining the parts. In addition, the grease must be resistant to the liquids or gases being handled. A large number of materials are employed in the manufacture of these products, and the selection of a grease is usually based on the valve manufacturer's recommendation. Most valve manufacturers have available lists of lubricants suitable for use with the more common chemicals and solvents.

Uses for Soap-Thickened Lubricants

When mineral oils are only slightly thickened with soap to a point where they remain fluid, the various grades are termed "nonfluid oils," or "semifluid greases." This type of lubricant is sometimes used where throw-off is encountered, as, for example, on chain drives, in various machine bearings, in textile mills, and similar applications.

Soap-thickened lubricating oils are not generally recommended for enclosed bearings and gears of the bath-oiled type on account of separation. This action is liable to occur either by centrifugal force, by oxidation of the soap content over a period of time, by elevated temperatures, or by a combination of these factors.

Soap-thickened lubricants are often a hazard in large plants unless an extremely rigid control over lubricants is exercised. They may be picked up and used on machinery where detrimental results, such as clogging of oil lines or wick feeds, will follow their use.

Extreme-Pressure Greases

The fourth group consists of soaps containing mineral oils that have been compounded with various film-strength builders, such as compounds of chlorine, phosphorus, sulfur, and other reactive agents.

There are many formulas for manufacturing extreme-pressure oils; and to manufacture greases, the extreme-pressure oil is simply thickened with soap. Extreme-pressure greases are widely used in the lubrication of antifriction roll-neck bearings, and much development work has been carried out with this type of bearing.

Roll-Neck Greases

In steel mills almost every type of grease and oil is used, but, in addition, special greases are manufactured for roll-neck bearings where heat, water, and scale are present. Roll necks are commonly equipped with sealed bearings supplied by circulating oiling systems, but sleeve types are very often cooled by direct jets of water and are designed with pockets to hold block greases of special grade.

Roll-neck compounds of this type are not generally true greases but are combinations of tallow, graphite, and heavy oil, or similar ingredients made into blocks. These blocks are cut to size, placed in the grease receptacles, and allowed to melt. Although the melting point is generally in the vicinity of 220° F, the rate of disintegration is controlled to a large extent by the consistency of the compound.

Grease Tests

For commercial requirements, the number of essential grease tests are few and simple. The following analysis is generally sufficient to form an opinion of the suitability of a grease for a particular service.

Type of soap base and percentage.
Viscosity of the oil and percentage.
Penetration (unworked).
Penetration (worked).
Melting point.
Fillers (if any).

Other tests may be stipulated, such as water content, ash, channeling, and ability to flow at low temperatures. For the last two tests there are several machines available, and so the particular one has to be specified if the characteristics are to be compared.

Penetration

Penetration tests are carried out with the instrument shown in Figs. 2 and 3. Figure 2 shows the penetrometer, and Fig. 3 shows the penetrometer cone. The test is intended to measure the consistency of lubricating greases.

The cone is calibrated in tenths of a millimeter, and in making the test the point of the cone is adjusted to just touch the surface of the sample. The plunger is then released and held free for 5 seconds. The depth of penetration is read on the scale and reported as unworked penetration or unworked consistency. The sample of grease is maintained at a temperature of 77° F, and readings are taken up to 400 hundredths of a centimeter or 4 millimeters. A semifluid grease will have a penetration of 355 to 400, while a hard-block type will have a penetration of 85 to 115. The association of the actual penetration with a grease will give a better sense of the grease consistency than the terms “soft,” “hard,” “stiff,” etc. In Chapter 14 on “Specifications” will be found a table showing the penetrations for the various consistencies of grease.

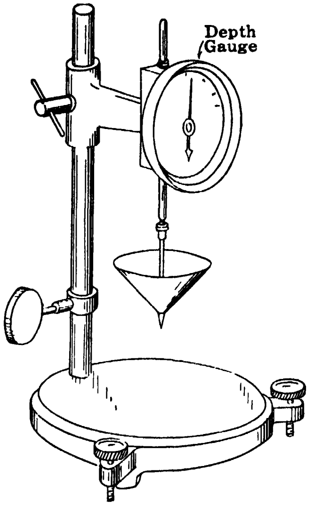


Fig 2. Penetrometer for testing the consistency of greases The term penetration is also used.

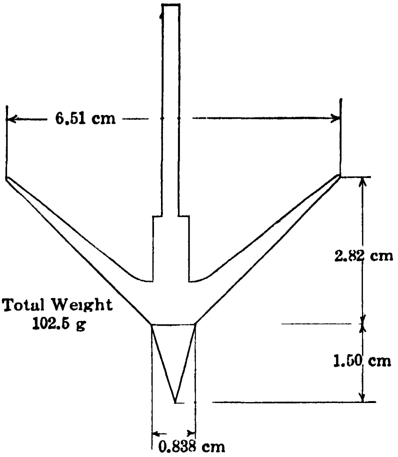


Fig. 3. Penetrometer cone.

Melting or Dropping Point

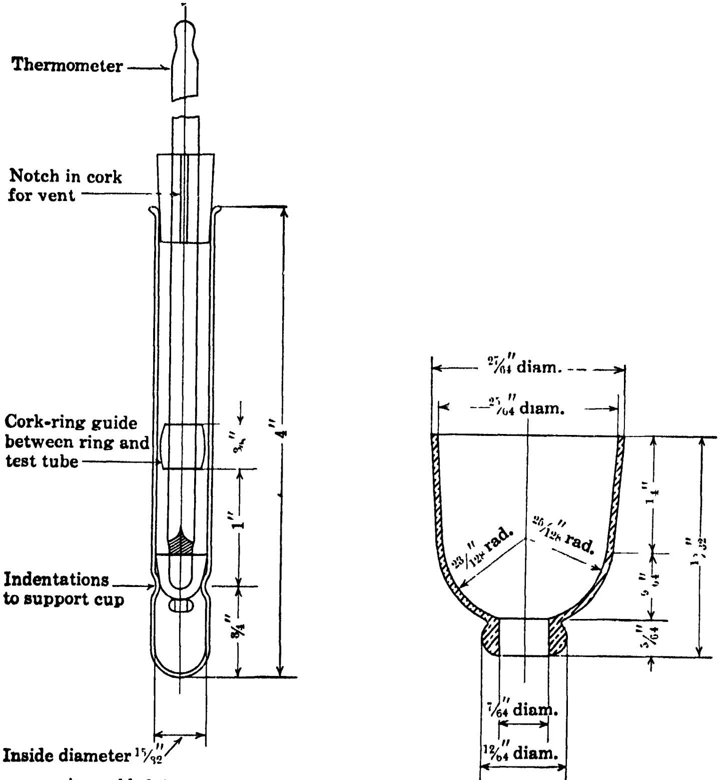
The dropping point of a grease is the temperature at which a grease passes from a plastic state to a liquid state.

This test is carried out under prescribed heating conditions wherein the first drop to fall from a cup is reported as the dropping point. The more common term employed is melting point, as, for example, in specifications where the melting point may be stipulated as 200° F, 250° F, and so on, depending upon the service requirements. Figure 4 shows the type of cup employed to hold the grease sample when making this test. This cup is suspended in a tube as shown and is immersed in a bath of oil which controls the temperature at which the grease melts.

The melting point of a grease does not determine the performance of the grease up to the melting point. The melting point is the temperature at which the grease liquefies and may be expected to run out of the bearing.

Unworked Consistency

The unworked (original) consistency of lubricating greases is influenced by a number of factors which are very difficult to control. The soap content is the most important factor, but the kind of fats used, the method of manufacture, the final water content, the rate of cooling, etc., are all important in determining the final consistency. Thus, it is impracticable to maintain the consistency within narrow limits. Any working or remelting of a grease after it is in the container will change the consistency. The consistency also changes on standing, most rapidly during the first 48 hours after manufacture.



Assembled Apparatus without Bath

Detail of Cup

FIG. 4. Apparatus for dropping point test of greases. The more common term is melting point.

Although many tests are based on the unworked consistency, this property very often bears no definite relationship to the worked consistency, which is the feature of practical importance for the softer grades of lubricating greases. Final tests should therefore be made for worked consistency.

On the other hand, very hard greases, such as certain steel mill and railroad greases, should be tested for the unworked consistency, which is generally the property of practical importance.

Worked Consistency

The worked penetration of a grease is obtained by first of all working the grease in the device shown in Fig. 5. The barrel is filled with a minimum inclusion of air and the grease worked with 60 double strokes of the plunger at a temperature of 73 to 77° F. Upon completion of this working, the grease is tested as before for penetration, at a temperature of 77° F, and the result is reported as worked penetration or worked consistency.

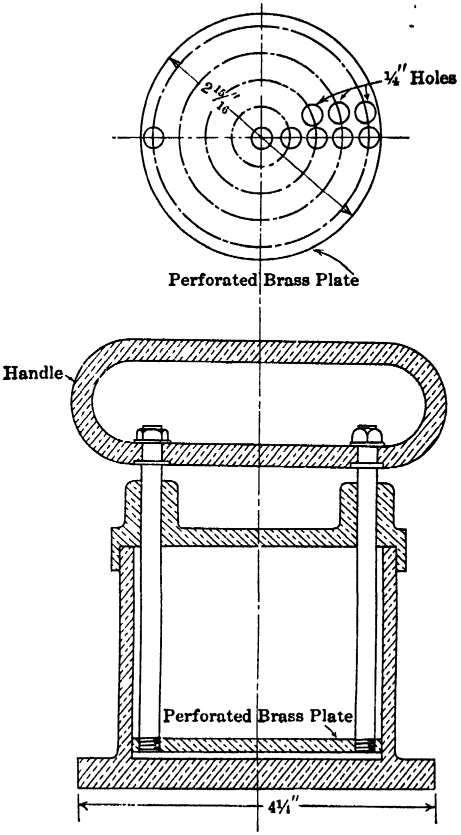


Fig. 5. Grease worker.

Oxidation Test

Greases are just as susceptible to the oxidation process as are mineral oils. This means that no grease is any more stable than the oil used in its manufacture. High-melting-point greases are often fortified with an antioxidant, but, even so, the deteriorating effect of heat and the catalytic action of contact with metals soon decomposes the grease. High-melting-point greases are generally of value where the temperature is not over 200° F, or where higher temperatures are only intermittent. At high temperatures frequent applications of grease are necessary.

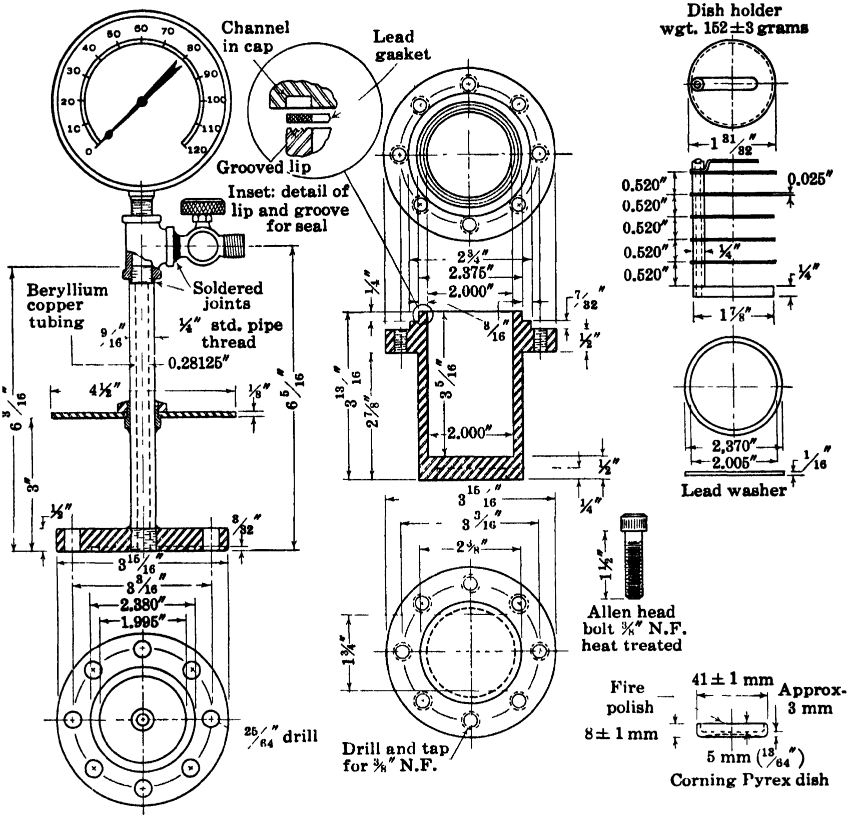


FIG. 6.

The oxygen-bomb test determines the resistance of the grease to oxidation under static conditions. It is therefore helpful in evaluating a grease that is to be used for bearings or machines that may be stored for a prolonged time. A sample of grease is oxidized in a bomb heated to 210° F and filled with oxygen at 110 psi. The drop in pressure over a given time determines the degree of oxidation. Figure 6 shows the essential parts of the apparatus.

Performance Tests

The performance of most greases is evaluated under actual service conditions. The many greases available, together with the variety of service conditions, makes it difficult to arrive at a standard of performance. Field tests are subject to a large number of variables which are difficult to control. This makes it difficult to compare greases.

The majority of electric motors are equipped with ball or roller bearings which are mostly grease lubricated. These, along with many pillow blocks, have similar requirements. Therefore, a great deal of interest has been shown in developing an accelerated test to evaluate ball- and roller-bearing grease performance.

The three most common tests are the General Electric, Westinghouse, and Navy. All of these depend upon running ball bearings with a definite amount of grease at a fixed speed and a controlled temperature. Even these tests require from 3 months to 3 years and repeated runs in order to eliminate any short runs due to the bearing. Heat is the principal means of accelerating the test. If raised too high it is unrealistic in that it does not simulate service conditions and the test results cannot be correlated with service. Many special tests, such as wheel-bearing and aircraft-control-bearing tests, are being investigated and used.

13

Synthetic Lubricants

All known materials have definite limitations of their physical and chemical characteristics. Mineral oils are no exception to the general rule. Some characteristics are well established, such as change in viscosity with temperature, low pour point associated with low viscosity, and high flash associated with high viscosity. The need for lubricants having less change in viscosity with temperature, low pour point with high viscosity, and high flash with low viscosity, among other characteristics, has been foreseen for some time. This need will be met by the synthetic lubricants. The value of these products for certain applications may be judged partially by the fact that they are economical when properly used and applied, even though the price may range from $2 or $3 per gallon to $500 or more per gallon.

The synthetic lubricants are in their infancy, and a great deal of research and field work is constantly being made. Two types of products have found volume acceptance in industry. These products are the polyalkylene glycols and their derivatives, and the silicones.

The silicones are manufactured from coal and sand. The silicone carbide formed is converted by suitable chemical means to silicone and oxygen, together with various organic radicals which are the silicone lubricants.

The polyethylene glycols comprise a series of polymers that have the general formula $HOCH_2(CH_2OCH_2)_xCH_2OH$. The lower-molecular-weight compounds are liquids, and the higher are waxlike solids.

An examination of the few physical characteristics tabulated in Table 1 will indicate how oils may differ.

A mineral oil to have a flash point of 600° F would have a viscosity above 3000 S.S.U. at 100° F. A pour point of -55 in a mineral oil would mean a viscosity under 100 S.S.U. at 100° F. In general, mineral oils have V.I.'s in the range of 0 to 110, while synthetics may be well above 140. Since these products are synthetics, they can be made with absolute uniformity in a wide range of characteristics. This is a dis-

TABLE 1

Lubricant	*Viscosity S.S.U. at 100° F*	*Flash, °F*	*Pour Point, °F*	*Viscosity Index*
Silicone	385	600	−55	
Ucon (polyethylene glycol)	385	430	−35	144
Mineral oil	385	420	0	0–110

tinct advantage, as we know the chemical structure with a great deal of certainty, whereas the molecular structure of mineral oils is so complex that we know its chemical structure only in the most general terms.

Synthetic Greases

Synthetic greases are composed of synthetic fluids and the same metallic soaps and thickeners that are used with the conventional mineral greases. Work is being carried on to develop more stable thickeners, as it is felt in some quarters that the fluids are more stable than the thickeners.

Instrument Oils

Instrument lubricants in general are not produced in great volume but nevertheless are extremely important. The requirements of a lubricant for instruments must be very carefully analyzed, as products offered for this use range from 50¢ a gallon to $500 or more. The synthetics should be very carefully investigated.

Compounding and Additives

Although the synthetics may be chemically satisfactory, they sometimes lack an affinity for metals and may lack load-carrying capacity under boundary lubrication. Therefore, they may need to have other materials added to give them the desired characteristics. Much the same types of additives and compounding materials as are used with mineral oils are being explored. The silicones are widely used as defoaming agents for mineral oils. As little as 1 three-thousandths of 1 per cent added to a mineral oil will almost always stop the oil from foaming. The silicones do not disperse well in mineral oils and therefore should be dispersed in a small volume of oil in a homogenizer or a Waring blender before being added to an oil system. Carefully estimate the quantity of silicone required, as too much may increase the foaming.

14

Specifications

Specifications for lubricants were originally developed, and are still being used, as the primary means of producing uniform products. For many years lubricants were chosen by brands, opinions, and experience, which worked reasonably well when requirements were simple. With the advent of the internal-combustion engine, electric motor, and steam turbine the demands upon the lubricant became more exacting. Technical data concerning the physical characteristics of the lubricants were soon required by the designers and users of equipment in order to forecast performance. The pioneering investigation of Howard Souther into motor oil viscosities, as reported in the *Association of Licensed Automobile Manufacturers' Report* 9 of August, 1906, did much to bring about S.A.E. crankcase oil specifications. His report indicated that motor oils of that time ranged from 43 to 154 S.S.U. viscosity at 210° F! Small wonder that early motorists were plagued with troubles. Today, with the petroleum industry working closely with engineers, we can operate equipment with the minimum of difficulties.

S.A.E. Numbers

One of the earliest systems, and even today the most widely used, is the S.A.E. (Society of Automobile Engineers) specifications. Through long usage of this system all purchasers of motor oil have acquired a sense of the proper viscosity for their purpose without having any idea as to the actual viscosity. It will be noted that the S.A.E. specifications cover only viscosity and make the broad statement that the oils listed are suitable for internal-combustion engines. The quality and performance are determined by the marketer's extensive specifications, block tests, and road tests. In Tables 1 and 2 are the viscosity ranges for S.A.E. crankcase and gear oils.

TABLE 1. CRANKCASE OIL SPECIFICATIONS

	Saybolt Seconds	
	0° F	
5W		Max. 4,000
10W	Min. 6,000	Max. 12,000
20W	Min. 12,000	Max. 48,000
	210° F	
20	Min. 45	Max. 58
30	Min. 58	Max. 70
40	Min. 70	Max. 85
50	Min. 85	Max. 110

TABLE 2. S.A.E. VISCOSITY NUMBERS FOR TRANSMISSION AND REAR-AXLE LUBRICANTS

S.A.E. No.	*Viscosity Range Saybolt Universal*	*Lubricant Must Not Channel at*
80	100,000 sec at 0° F max.	−20° F
90	800 to 1500 sec at 100° F	0° F
140	120 to 200 sec at 210° F	35° F
250	200 sec at 210° F min.	....

From the tables it will be noticed that motor oils are numbered from 5W to 50, and gear oils are numbered from 80 to 250. From this sequence it might be assumed that all gear oils are more viscous than all motor oils, but this is not so. The two systems overlap at some points, and the overlapping S.A.E. numbers are compared in the following table:

S.A.E. Numbers for Gear Oils *	*Equivalent S.A.E. Numbers for Motor Oils*
80	30
90	40 and 50
140	Heavier than any motor oil
250	classification

* This table does not take into consideration the qualification of channeling applied to gear oils.

The limiting crankcase temperatures for motor oils were determined from practical and known factors. For example, a viscosity of 40,000 seconds is a practical maximum for starting a motor at 0° F. At a temperature of 0° F the output of a battery is materially lowered and gasoline has poorer volatilization qualities; hence the viscosity should be under 40,000 seconds at 0° F, or 10W lubricating oil should be used for low starting temperatures. For temperatures that are fairly consistently below 0 a 5W oil should be used in preference to diluting 10W oil with fuel.

In similar manner, an S.A.E. 80 gear oil is essentially a low-temperature lubricant. The S.A.E. 140 and 250 gear oil ratings are designed for heavy-duty lubricants, and viscosity limits are therefore stipulated at a temperature of 210° F without regard to low-temperature characteristics. The S.A.E. 90 rating is an intermediate gear lubricant requiring characteristics between S.A.E. 80 and S.A.E. 140.

In actual practice the operating results secured by these ratings may vary considerably because mechanical conditions are not uniform for automotive equipment, and obviously the ratings are based on all working parts' being in good repair.

Gear Lubricants (A.G.M.A.)

The American Gear Manufacturers Association has developed specifications for the preferred gear lubricants, based on viscosity. Duplicating the S.A.E. practice, only viscosity and type of compounding are specified. The quality and suitability of the lubricant is the responsibility of the supplier. Table 3 shows the A.G.M.A. numbering system.

Table 3

	A.G.M.A. Saybolt Viscosity Range			*Mild Extreme-Pressure Lubricants*	
A.G.M.A.	*100° F*	*210° F*	*A.G.M.A.*	100° F	210° F
1	150– 280		1	150– 280	
2	280– 360		2	280– 360	
3	490– 700		3	490– 700	
4	700–1000		4	700–1000	
5		80– 105	5		80–105
6		105– 125	6		105–125
7		125– 150	7		100–125
7	Compounded	125– 150	8		100–190
8		150– 190			
8	Compounded	150– 190			
9	For open gears	350– 550			
10	For open gears	900–1200			
11	For open gears	1800–2500			

Turbine Manufacturers' Specifications

The steam turbine builders and the oil suppliers have agreed upon the specifications in the following table. It will be noted that this specification calls for rust protection and stability, in addition to the

		A.S.T.M. Test	
Grade	*Viscosity S.S.U. at 100° F*	*D942-47T Rust*	*D665-49T Oxidation*
Light	140–160	Pass	Pass
Medium	290–320	Pass	Pass
Heavy	450–550	Pass	Pass

proper viscosity. Oil suppliers, turbine builders, and operators of turbines all cooperated in the development of this specification. The specification appears simple. However, to correlate the tests with service and to arrive at a fair interpretation of results required some 12 years of intensive work.

National Lubricating Grease Institute Specifications

The N.L.G.I. is an organization whose membership is made up of grease manufacturers. This organization has set up a series of numbers which define grease by worked penetration. No other information is included in the specification. The accompanying table sets forth the numbering system.

Consistency Number N.L.G.I.	*Description and Use at Normal Room Temp.*	*Worked Penetration A.S.T.M.*
0	Semifluid	355 to 385
1	Very soft: grease gun	310 to 340
2	Soft: grease gun	265 to 295
3	Grease cup	220 to 250
4	Grease cup	175 to 205
5	Grease cup, block type	130 to 160
6	Block type	85 to 115

Government Specifications

Many branches of the armed services and the Treasury Department issue specifications for the procurement of lubricants. In general, these specifications are more extensive than those employed by industry, as an attempt is made to write performance into the specification. This can be done only at great expense in full-scale tests or simulated tests. One factor to be borne in mind is that the government normally has to purchase from the lowest bidder whose lubricant meets the tests. Private industry can procure lubricants from whichever of the many responsible suppliers it cares to deal with, and therefore requires only the minimum in specifications. Table 4 covers aircraft-engine oil specification.

TABLE 4. AIRCRAFT-ENGINE LUBRICATING OIL SPECIFICATIONS

Specification MIL-O-6082	*Grade Designation*			
Requirement	*65 (1065)*	*80 (1080)*	*100 (1100)*	*120 (1120)*
Flash point, °F, min.	420	450	470	490
Pour point, °F, max.	0	0	+10	+20
Diluted pour, °F, max.	. . .	−65° F	−65° F	. . .
Viscosity, S.U.S., at 210° F	62–68	76–84	93–103	115–125
Viscosity index, min.	100	100	95	95
Carbon residue, %, max.	0.6	0.9	1.2	1.5
Sulfur, wt. %, max.	0.5			
Corrosion, copper strip at 212° F	No black or brown discoloration or pitting			
Precipitation no.	0			
Saponification no., max.	0.5			
Neutralization no., max.	0.10			
Ash, %, max.	0.0025			

Table 5, reported in the Texas Company publication, *Lubrication,* Vol. 34, No. 4, shows a typical analysis of gas turbine oils.

TABLE 5. TYPICAL TESTS OF AIRCRAFT-GAS TURBINE LUBRICATING OILS

	AN-O-9, Grade 1010	*AN-O-8, Grade 1065*
Flash, C.O.C., °F	300	460
Fire, C.O.C., °F	335	520
Pour, °F	−70	0
Viscosity, S.U.S.		
at −40° F	12,936	. . .
at 100° F	59.4	530
at 210° F	34.5	67
Viscosity index	66	103
Sulfur, %	0.05	0.15
Neutralization no.	0.02	0.01
Carbon residue, %	0.02	0.14
Ash	None	None
Corrosion		
Cu, Fe, Al, Mg	O.K.	. . .

15

Bearing Lubrication and the Formation of Oil Films

Bearings may be divided into two general types, "plain" and "antifriction." The first involves frictional surfaces sliding over each other, and the second involves the separation of moving surfaces by balls or rollers. This latter method substitutes rolling friction for sliding friction. This discussion covers plain bearings only. Antifriction bearings will be discussed in a succeeding chapter.

Bearings may also be classified as either radial or guide, depending upon whether the motion of the moving part is rotary or reciprocating. Bearings that carry a thrust load are known as thrust bearings.

Friction cannot be entirely eliminated, and the object of lubrication is to reduce it as much as possible. Friction may be reduced through the use of lubricants by the following methods:

1. A fluid film may be interposed between the two opposing surfaces which entirely prevents metallic contact and substitutes fluid friction for the solid friction that would otherwise occur. This condition is known as fluid-film lubrication.
2. The lubricant may serve primarily to fill in surface imperfections and reduce friction by making the opposing surfaces smoother or more slippery. This is known as boundary lubrication.
3. Under very heavy pressures the lubricant may react chemically with the metal surfaces and maintain a plating action which tends to prevent seizing of the opposing surfaces. This is known as extreme-pressure lubrication.

Until petroleum lubricants became available, fatty oils and fats were universally used. Little was known of the mechanism of lubrication until the year 1883. Before that time it was generally assumed that all lubrication was of the boundary type. The original fluid-film theory was an accidental observation.

In 1883 Beauchamp Tower, an Englishman, was investigating the various effects of changing the methods for oiling a railway journal bearing, and at one point had drilled a hole in the load area of the bearing, preparatory to applying oil by a lubricator. Figure 1 is a schematic drawing of Tower's experimental set-up. The experiment failed, and Tower drove a wooden plug into the oil hole. When the bearing was again placed in operation, Tower noticed oil coming from the plugged hole, and much to his annoyance the plug kept coming out no matter how tightly he drove it in. Tower quickly grasped the fact that the hydraulic pressure must be very high.

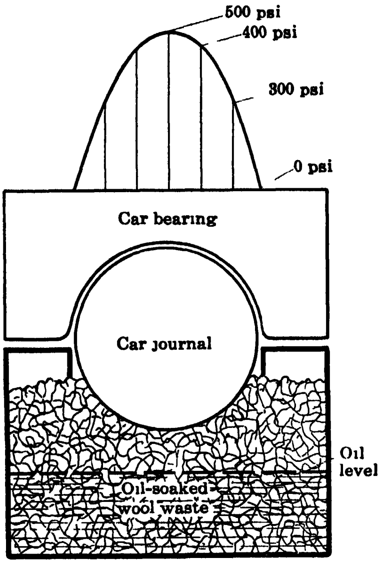


Fig. 1.

Tower published the results of his discovery in 1883, and Osborne Reynolds, another Englishman who had been investigating the phenomena of lubrication, followed with a mathematical analysis of the hydrodynamic theory and in 1886 published his classical paper, "The Theory of Lubrication and Its Application to Mr. Beauchamp Tower's Experiments." This paper included a remarkable analysis of fluid-film lubrication, along with an equally remarkable mathematical interpretation.

Hydrodynamic Theory of Lubrication

The hydrodynamic theory of lubrication, involving the complete separation of opposing surfaces by a fluid film, is easily understood when the mechanism of oil film formation in a sleeve bearing is known. Figure 2 illustrates a journal *J* at rest in a bearing *B*, the space *C* being the clearance between the bearing and journal (shaft). Clearance is necessary to allow the formation of an oil wedge to lift the journal. In the attached sketches the clearance is greatly exaggerated for the purpose of illustration. In actual practice the clearance generally amounts to approximately one-thousandth of an inch per inch of journal diameter. As bearing clearances approach zero, the surfaces of the journal and bearing become nearly parallel. Parallel surfaces are in-capable of forming fluid films. Therefore there is an optimum clearance for a given speed and load. From the diagrams in Fig. 4 a graphic analysis of fluid-film lubrication may be obtained. In both *A* and *B*, *X* is moving at a constant velocity, carrying an oil film, and *Y* is stationary. In part *A*, *X* and *Y* are parallel, while in *B* the surfaces of *X* and *Y* are at a slight angle. In both parts the triangle *abc* represents the quantity of oil entering between the surfaces, and *a′b′c′* represents the quantity of oil leaving. In part *A*, *bc* equals *b′c′*, and *ac* equals *a′c′*; therefore the triangles are equal, and the quantity of oil entering the bearing equals the quantity leaving. There is therefore no upward force to separate the surfaces *X* and *Y*. In part *B*, *bc* is greater than *b′c′*, and *ac* equals *a′c′*; therefore, triangle *abc* is greater than triangle *a′b′c′*. This shows that more oil is entering than is leaving. This results in a vertical force which tends to separate *X* from *Y*.

In both *A* and *B* there is a horizontal force shearing the oil, but only in *B* is there a resultant vertical force. This simple basic principle is why we must design moving surfaces to provide a wedge if we are to have fluid-film lubrication and if our machinery is to carry high loads without wear.

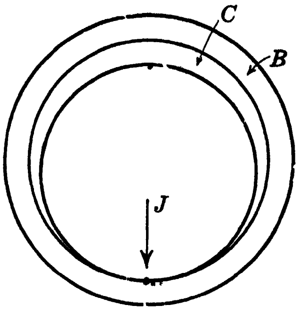


Fig. 2. Journal at rest in a bearing. No oil in the pressure area.

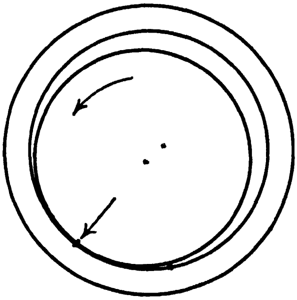


Fig. 3. Journal starts to turn, and owing to solid friction climbs up side of bearing to the left. In the meantime oil fills into space at right which was formerly dry. Under its own weight, journal tends to fall back into former position and lands on oil film.

In Fig. 2 the arrow indicates the direction of the load with the journal at rest. Practically all the lubricant has been squeezed from the load area. When rotation starts, with the clearance space full of oil, the journal has a tendency to climb or roll up the left-hand side of the bearing, owing to solid friction. The area of contact at this stage is shown by the arrow in Fig. 3. Now the center of the bearing does not coincide with the center of the journal; hence it tends to slide back, and in the meantime the clearance space fills with oil in the former load area. Because oil is adhesive and sticks to the journal, rotation causes oil to be drawn into the wedge-shaped space to the left of the load area. As the speed of rotation increases, more oil is carried into the wedge by the revolving journal, and sufficient hydraulic pressure is soon built up to completely separate the journal from the bearing. When this film has formed, the journal assumes the position shown in Fig. 5*A*. However, the pressure built up in the converging oil wedge tends to push the journal to the other side of the bearing, and the final operating position of the journal is shown in Fig. 5*B*. Figure 6 shows the pressure distribution in an oil film with the length of each radial line representing the pressure at that point. It will be noticed that as soon as the maximum oil pressure area is passed, there is a sharp decrease in pressure, and at the point *A* in Fig. 6 there is actually a suction effect instead of pressure.

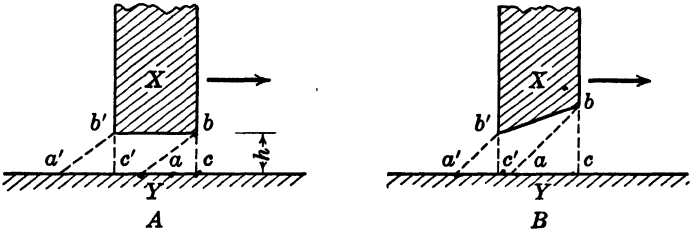


Fig. 4.

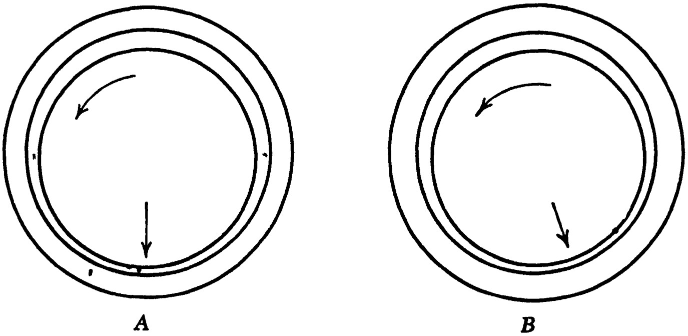


Fig. 5. *A*, journal is now turning faster and drawing oil into the pressure area. *B*, oil film is now completely formed. Journal floats in a slightly eccentric position, owing to built-up hydraulic pressure at left.

The principal characteristics determining fluid-film lubrication are viscosity, rubbing speed, and load. The relationship among these factors is shown graphically in Fig. 7.

f = Coefficient of friction
z = Absolute viscosity
N = Speed in revolutions per minute
P = Load in pounds per square inch

$$f = ZN/P$$

As can be seen from the curve in Fig. 7, a high coefficient of friction results with a low ZN/P, and wear is likely to occur. There is an optimum value for a low coefficient of friction above which the coefficient of friction rises as the oil film becomes thicker. At very high values of ZN/P the friction becomes excessive and erratic, owing to turbulence within the oil film.

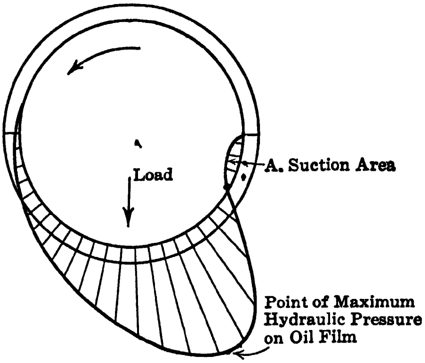


FIG. 6. The length of each line represents the hydraulic pressure at that point. Notice how the pressure falls off at the right until a slight vacuum is formed at A.

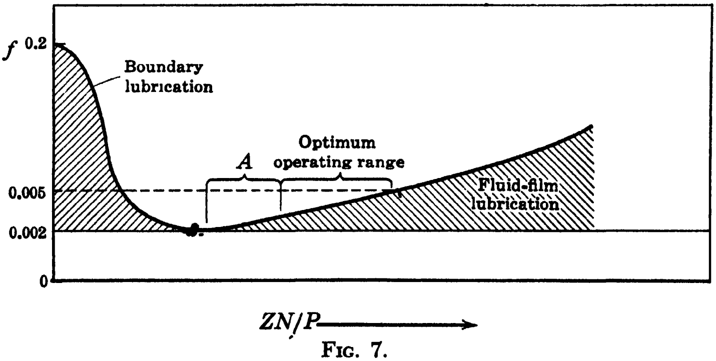


FIG. 7.

In designing a sleeve bearing it is most desirable to have the bearing perform in the "optimum range." The speed and load are usually fixed, so that the only way to change the oil film characteristics is by viscosity. This is why great emphasis is placed upon the viscosity of a lubricating oil. From the basic relationship ZN/P, it will be seen that a low viscosity and a low speed are conducive to causing the bearing to run in the undesirable boundary lubrication range unless the load is extremely light. As the loads become high the speed and viscosity must be increased to permit the bearing to run with a fluid film and low friction. Too high a viscosity coupled with high speed causes high friction and high running temperatures in a bearing.

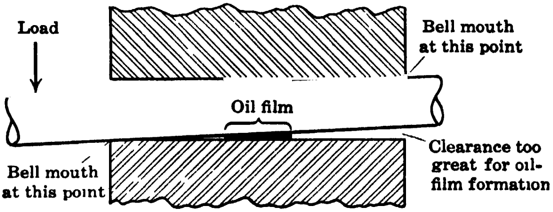


Fig. 8.

In most designs the shaft size is selected so as not to exceed permissible shaft deflection under the maximum load. A machine designer might be tempted to reduce his unit bearing load by increasing the length of the bearing. There is little to be gained by extending the bearing beyond 1½ times the shaft diameter, as bending of the shaft only wears the bearing bell mouthed, with reduction in bearing area. Figure 8 illustrates the fallacy of relying upon long bearings to reduce bearing loads.

In order to obtain fluid-film lubrication the following conditions must be fulfilled.

1. The lubricant must be capable of "wetting" the journal and bearing so that the oil will adhere to the revolving journal and be drawn into the pressure area.

2. The bearing and journal must be free to assume a slight angle to permit the formation of a converging oil film. It is not possible to obtain fluid-film lubrication between two parallel flat surfaces because an oil wedge cannot be built up.

3. The clearance space between the bearing and the journal must be kept full of oil.

4. The lubricant must be applied in the low-pressure area of the bearing.

5. The viscosity of the oil must be sufficiently high to permit the formation of a load-supporting oil film under the prevailing conditions of load and speed.

6. There is a minimum rubbing speed below which a full fluid oil film cannot be provided. This condition accounts for most of the wear in bearings which stop and start frequently.

The film separating a bearing and journal may be regarded as many layers having relative motion with respect to one another. One layer clings to the stationary bearing and another to the revolving journal, while in between are other layers in sliding contact which are being continually sheared. The relative movement of these layers results in the creation of fluid friction and consequent heat, which becomes greater as the oil viscosity is increased beyond that necessary to secure a floating journal.

High speeds increase the thickness of oil films owing to the increased pumping action of the journal. This operating condition permits the use of relatively light oils, regardless of the weight or pressure on the bearing. Slow speeds decrease film thickness and require relatively heavy oils.

In spite of the fact that oil films can support very heavy loads they are very thin. In modern industrial machinery the film thickness ranges from 0.0002 (two ten-thousandths) to 0.004 (four thousandths) of an inch. An average oil film is about one thousandth of an inch thick in the pressure area of a bearing.

In speaking of oil-film thickness of 0.0002 inch it is well for the lubrication engineer to bear in mind to provide an oil film greater in thickness than the maximum deviation of surface irregularity. Otherwise the high spots will pierce the oil film with consequent wear, scoring, or seizing. If a thick oil film cannot be provided, surfaces of journals and bearings must be highly finished.

Much of the wear that occurs in the bearings of machines takes place during starting and stopping. To prove this point we might cite the large turbines that rotate continuously for years with no significant wear. The same turbine that is on stand-by service, with starts and stops, generally shows about a thousandth of an inch of wear per year.

Boundary Lubrication

When conditions of bearing design, speed, load, and method of application of the lubricant are not favorable to the formation of an oil film, the state of lubrication is known as boundary lubrication. In this case there may be intermittent contact between the bearing and journal, and the laws of fluid-film lubrication are not applicable. The lubricant merely serves to make the opposing surfaces more slippery and to fill in surface imperfections. For slow speeds and heavy loads "oiliness" or film strength of the lubricant is an all-important factor. These conditions of operation indicate that a mild extreme-pressure, a grease, or a solid lubricant should be used. The mild extreme-pressure and the greases, being polar compounds, provide greater wetting ability than conventional oils. The solid lubricants should be used only under special conditions.

Oil Grooves in Bearings

Grooves are frequently employed in the top half of the bearing or nonpressure area for distributing the lubricant evenly ahead of the pressure area. Grooves in the actual pressure area are considered harmful because they tend to disrupt the oil film and reduce the size of this area.

The ability of an oil film to lift and support a heavy load is dependent upon hydraulic pressure. This pressure is brought about by the pumping action of the rotating journal, and any grooves in the pressure area which permit oil to escape will tend to encourage metallic contact. Also, when bearings are composed of two or more parts fitted together, any sharp corners at the joints will tend to scrape the oil from the journal, and, consequently, all corners and edges should be chamfered or rounded to prevent this scraping action.

The principles of correct design and grooving of bearings may be briefly summarized as follows:

1. Use grooves only where necessary for longitudinal distribution of the lubricant along the journal.
2. Do not cut grooves in the pressure area.
3. Chamfer or round off all sharp edges of bearing segments or grooves to prevent scraping the lubricant from the journal.
4. To minimize end leakage, grooves and chamfers should extend only to within ½ inch of either bearing end.
5. Locate the point of application of the lubricant in a portion of the bearing that is not under pressure.
6. Heavily loaded slow-speed bearings should have the point of application of the lubricant closer to the pressure area than is required in higher-speed and more lightly loaded bearings. Where this is not

possible, an auxiliary groove placed slightly ahead of the pressure area may be required to improve distribution. Figure 9 shows the type of groove necessary for the average bearing. Figure 10 shows the type of grooving most suitable for heavy duty slow-speed bearings. Figure 11 shows the type of grooving that is highly detrimental in the pressure area of a bearing. This type of grooving merely serves to cut down the actual bearing area and allows the oil under pressure to escape. Another detrimental effect of grooves in the pressure area is that, as the bearing wears, the chamfer is reduced to a sharp edge, which acts

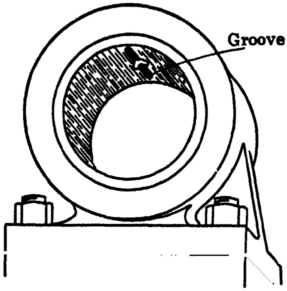


Fig. 9. Approved type of oil groove in bearing. Groove should be cut to within about ¼ to ½ inch at each end.

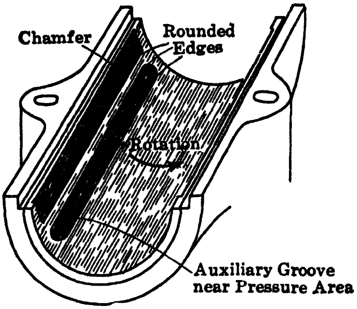


Fig. 10. In low-speed heavy-duty bearings it is usually desirable to cut an auxiliary groove in the lower half of the bearing, just ahead of the pressure area, in order to assure a full supply of oil along the length of the bearing at that vital section.

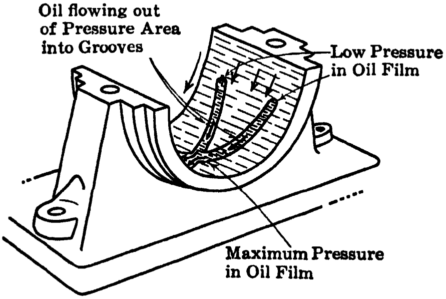

Oil flowing out of Pressure Area into Grooves
Low Pressure in Oil Film
Maximum Pressure in Oil Film

Fig. 11. Grooves in the pressure area permit the oil to take the path of least resistance, namely, into the grooves themselves instead of between the surfaces of the journal and bearing. Such grooves may result in the complete loss of an adequate oil film.

as a scraper and increases the rate of wear. Figure 12 shows the effect of such grooves on the distribution of oil pressure.

The usefulness of grooving in waste-packed journal bearings is also very doubtful. When chamfered along the side to give a free passage for the oil wedge, this type of bearing will function better without grooving.

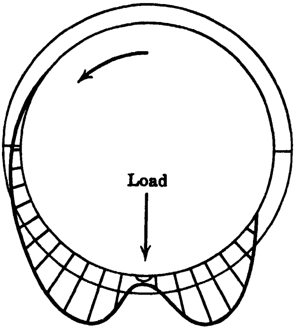


Fig. 12.

Hot Bearings

There are two classes of hot bearings. One is caused by induced heat in such mechanisms as steam-heated rolls, electrode shafts, and oven conveyors. In this class of bearings the lubricant does not play a significant part in the bearing temperature. Cooling must be obtained by circulating a large volume of oil, incorporating an oil cooler in the circuit, or using cooling water or air. Sometimes the source of the heat can be insulated from the bearing.

The second class of hot bearings are those in which the established or predetermined operating temperature deviates radically under standard operating conditions. In these cases the full fluid oil film has been destroyed and the bearing is on boundary lubrication, with resulting higher coefficient of friction. The major causes of this type of failure are:

1. Loss of oil supply due to:
   a. Low oil level.
   b. Excessive clearance in the bearing.
   c. Pump or oil ring failure.
2. Loss of bearing area due to corrosion or fatigue of the bearing metal.
3. Misalignment caused by overload which deflects the shaft and sometimes caused by changes in floor loads.
4. Improper viscosity of the oil.
5. Improper oil grooving.

Cooling Bearings

To reduce the temperature of an overheated bearing it is necessary to determine the cause. Loss of oil supply is easily determined, and the remedy obvious. If the cause is excessive clearance the geometry of the bearing is altered to such an extent that a thick oil film cannot be maintained. Temporarily a much higher-viscosity oil may be helpful until the bearing can be renewed. Loss of bearing area can be corrected only by replacing the bearing at once. With misalignment the load becomes so high on a small portion of the bearing that a thick oil film cannot be maintained. If the cause of the misalignment cannot be corrected at once, and many times it cannot, the geometry of the bearing must be changed. This can be done while the equipment is running. The best method is to mix a paste or semifluid of oil with mica or talc, or some other mildly abrasive material. This mixture is fed into the bearing until it has cooled down, and then the bearing is flushed copiously with oil. The lapping compound will increase the clearance at the tight spots and will not alter the clearance where thick film lubrication is present. In fact this procedure greatly hastens the fittings of rather large bearings to worn journals. To reduce the tendency of scoring and to aid in restoring the bearing surfaces, the E.P.'s are frequently employed and are often effective. In all cases of insufficient bearing clearance, rapid cooling of the bearing housing is liable to decrease the clearance further by shrinking the housing onto the journal. Every effort should be made to cool through the shaft. Remember that in cooling large bearings it may be hours before any appreciable reduction in temperature is observed, even after the cause has been corrected, because of the heat capacity of the bearing, housing, journal, and structural members. Never accept hot bearings as a necessary evil. There is always a reason for them, and the cause should be determined and corrected. The practice of running compressors or engines at low speed should be discouraged, as the rubbing speeds are too low to form thick oil films.

Thrust Bearings

The purpose of a simple collar-thrust bearing is to prevent a revolving shaft from moving lengthwise in either direction. (See Fig. 13.) This particular design of thrust bearing is sometimes employed on marine engine propeller shafts to counteract the forward force imparted by the propeller, on pulp shredding machines in paper mills, and for a large number of similar machines.

Owing to the fact that the collars and the bearing surfaces make straight-line contact with each other, there is no provision for the formation of an oil wedge, and lubrication is therefore of the partial or boundary type. Relatively heavy oils are required to lubricate straight collar-thrust bearings, and a small percentage of animal or vegetable oil is desirable to increase the load-carrying ability of the oil films.

This type of thrust bearing is rapidly being displaced by more efficient types. Their unsatisfactory load-carrying capacity, the large number of collars required to carry loads, and their high coefficient of friction, which requires considerable power and develops so much heat that cooling is required, are all reasons why this type of thrust bearing should not be used. It should be used only where intermittent thrust of low magnitude occurs.

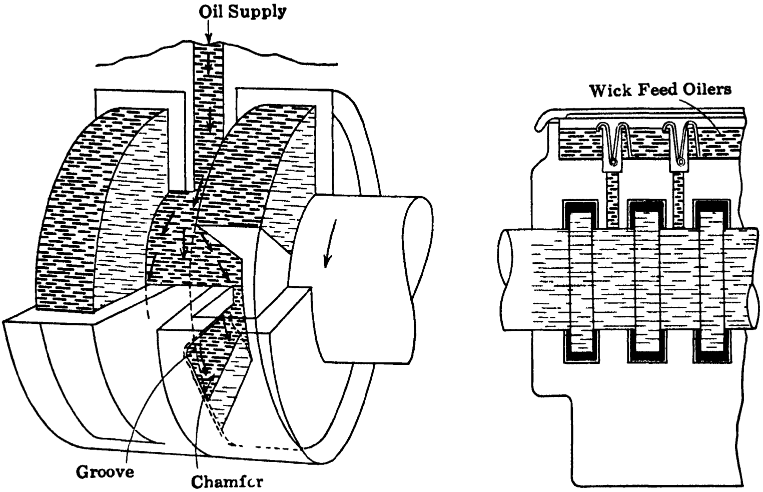


FIG. 13. Plain type of collar thrust bearing. Boundary lubrication is present in simple collar thrust bearings. The proper method of lubricating a collar thrust bearing is to introduce the oil between the collars so that centrifugal force throws the lubricant outward across the thrust surface. The distribution of lubricating oil over each bearing is materially assisted by radial grooves and the chamfering of these grooves in such a manner that oil wedges are formed just ahead of the pressure areas.

The most interesting designs from the viewpoint of lubrication are thrust bearings adapted to employ the complete theory of oil-wedge formation. Figure 14 shows a Michell thrust beáring which is a practical application of the theory explained by Reynolds in 1886.

This type of bearing consists of pads which are free to rock on a pivot. When the collar revolves, the oil is dragged between the two rubbing surfaces, hydraulic pressure quickly builds up, and the pads conveniently tilt to accommodate the necessary oil wedge. So perfect is this design in its agreement with theory that Babbitt metal may be crushed on the face of the pads before the oil film will fail. This generally occurs under loads of about 4 to 6 tons to the square inch.

Bearings adapted to taking up a natural wedge position with respect to the oil film are employed on the shafts of steam turbines, centrifugal pumps, and similar machines where heavy thrust loads are encountered.

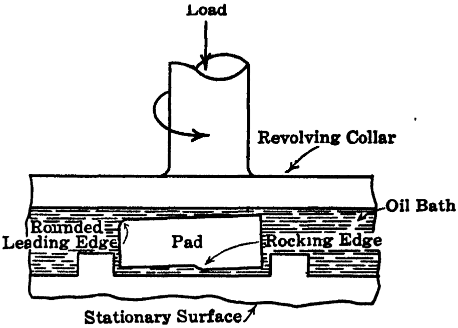


Fig. 14. Michell thrust bearing. The principle of oil-wedge formation is employed in this thrust bearing. The leading edges of a series of tilting pads permit the formation of wedges of oil as soon as the moving collar begins to turn. At full speed complete oil films are formed between the pads and the collar.

Figure 15 shows the principle employed in a Kingsbury bearing. The design is similar to that of the Michell bearing, except that the pads rest on pivots.

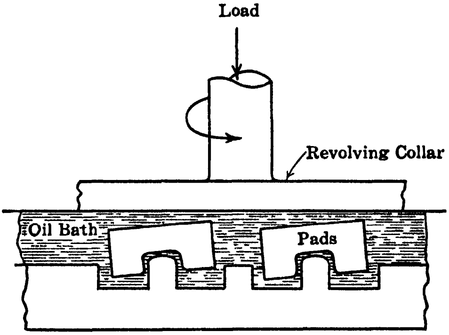


Fig. 15. Kingsbury thrust bearing. The principle of operation is the same as for the Michell bearing.

Figure 16 shows the principle employed in a Gibbs thrust bearing. In this design the stationary surface is divided into sectors. Each sector is divided by an oil groove and is beveled to conform with the speed and load conditions to establish the proper oil wedge.

The Gibbs bearing has a fixed angle of attack for the oil film which depends to a large extent upon beveling to form oil wedges. The limitations of design for this bearing are such that it will perform at maximum efficiency only under one combination of speed and load. However, it will function safely under wide speed and load variations.

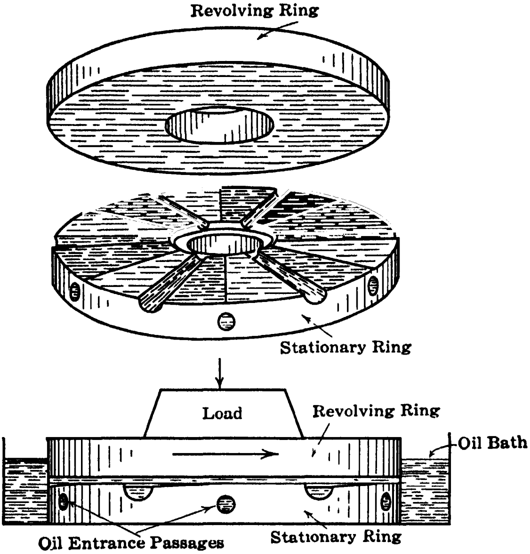


FIG. 16. Oil-wedge film formation as utilized in the Gibbs thrust bearing. This bearing comprises a revolving ring and a stationary ring. The revolving ring offers a flat thrust surface, while the stationary ring is grooved radially and half of each intervening sector is beveled toward the groove. When the bearing is operating, the oil in the grooved and beveled portions of the stationary ring is drawn into the pressure areas, thus forming complete surface-separating films. Circulation of the oil is effected by the natural creation of centrifugal force, which throws oil outward from the bearing areas, thus creating a suction which draws oil through the radial holes and into the core.

These bearings are used in boiler feed pumps, horizontal steam turbines, and equipment where the thrust is low at the start and builds up as the speed increases.

The Kingsbury and Michell bearings with their tilting pads accommodate themselves to the formation of efficient oil films under all speed and load conditions. This feature makes them of extreme value where high starting thrusts are encountered, as in hydraulic turbines. The automatic adjustment makes it possible for them to lift the surfaces apart with an oil film in a partial revolution of the shaft. Also, in high-speed high-thrust loads, the savings in power by having the bearing always running efficiently more than compensates for the higher initial cost of such a bearing.

Bearing Materials

Almost all known materials have been used as bearings in some form or other. The ideal bearing material would be one that would:

1. Be inexpensive and readily available.
2. Resist plastic deformation and fatigue under load.
3. Prevent shaft wear.
4. Have a high rate of heat transfer.
5. Have a low coefficient of friction.
6. Resist corrosion.
7. Be easily wetted by lubricants.

To date no one bearing material has all the desirable features. The choice of bearing materials depends upon obtaining the maximum of desirable characteristics and the minimum of undesirable.

Babbitt metal is one of the most widely used bearing materials. The original formula developed by Isaac Babbitt for bearing metal was approximately 89 per cent tin, 7 per cent antimony, and 4 per cent copper. Babbitt was a silversmith by trade, and, during all the years since his invention, no alloy has been found that is actually superior in every way. In fact, this formula is still considered to be among the best known, and rates high in service life.

Thick Babbitt bearings are becoming obsolete, as the liners tend to break away from the casting, are subject to plastic flow, and tend to crack easily, owing to the difference in coefficients of expansion; and bearings have to be replaced, as a rule, after a few thousandths of an inch of wear. Babbitts in which lead has been substituted for most of the tin are known as lead-base. Babbitts containing less than about 7 per cent tin are unreliable. It is important, when evaluating the failure of a bearing, that its analysis be known.

The builders of internal-combustion engines have developed some alloy bearings such as copper-lead and cadmium-silver-copper. These bearings are resistant to cracking away from the liner but at the expense of being subject to corrosion. The proper lubricant plus control of temperatures will prevent corrosion. The lubricant should contain a lead passivator, and temperature should be kept below 250° F.

Bronzes are widely used as bearing materials where high loads or boundary lubrication are likely to occur. Shafts are normally hardened to lessen damage in event of bearing failure. The high-lead bronzes are easiest on the shaft.

Cast iron makes a good bearing material under light loads. It requires a careful run in period, and a lubricant failure usually results in severe damage to the shaft and bearing. As this is a very hard material, alignment and surface finish must be good.

If steel is used as a bearing it is important to have both the shaft and the bearing hardened. There should be a Rockwell scale difference of about 15 points in hardness between the two.

Porous bearings are constructed from powdered metals compressed and sintered. This leaves a porous structure, and the voids are filled with oil under a vacuum. The oil from the bearing wets the shaft, and the bearing operates under boundary conditions. For light duty the bearings may last the life of the equipment. For continuous operation provision must be made to supply additional oil to the bushing. Generally an oil reservoir in the housing will supply oil through the wall of the bushing to the shaft. High temperatures, either induced or caused by load and speed, will oxidize the oil in the pores of the bushing and will plug the pores, with consequent bearing failure.

Carbon, carbon metal, ceramics, and many other materials are used as bearings for special purposes.

Nonmetallic Bearings

Most nonmetallic bearings have the following characteristics:

1. The materials are insulators and have poor heat transfer.
2. They lack dimensional stability, so that generous clearance must be provided for.
3. They are organic materials and decompose at low temperatures.
4. They are resistant to attack by many chemicals.
5. They resist abrasion and shaft scoring.
6. They require a generous supply of coolant or lubricant.

Wood was one of the earliest bearing materials and is still used. Hard maple may be used where oil is the lubricant, and lignum vitae is used in the presence of liquids such as water.

Many plastics are offered as bearing materials, and are used most in the chemical industry.

Under loaded conditions the large volume of coolant required dictates that the liquid in which the bearing is operating be used as the lubricant. An example of this is the stern tube bearing on a ship.

Bearing Failures

Bearings fail for various reasons. Lubrication is frequently assumed to be the cause, and, although bearings fail because of the loss of the oil film, the contributing cause may have little to do with the lubricant.

1. Closely fitted precision bearings have restricted oil flow and run on thin-film lubrication. If the bearings are fitted too closely the shaft, upon starting up, warms up faster than the bearing and the clearance is taken up, with consequent loss of the oil film. If the bearing is suddenly cooled it frequently shrinks onto the shaft, with consequent failure.
2. Too large a clearance, so that end leakage becomes greater than the rate of supply, with resulting oil starvation in the pressure area.
3. Misalignment or deflection of shafting which crowds the corners of the bearings. This condition is usually recognizable by the bell-mouth wear of bearings.
4. Fatigue and cracking out of portion of the bearing liner.
5. Deformation due to pressure, causing plastic flow of bearing liner. Remember that most bearing materials lose strength as temperature rises. This is particularly true of the softer alloys, such as Babbitt metal.
6. Corrosion causing pitting of bearing, which reduces the load-carrying area.
7. Contamination of lubricant with foreign material.
8. Lack of lubricant due to oversight, leaky housing, plugged oil line, etc.
9. Incorrect location of the oil supply to the bearing.
10. Improper oil grooving.
11. Applying the improper type of lubricant.
12. Poor mechanical assembly.

When examining a bearing failure, an engineer should not be surprised to find a generous supply of new lubricant. The most common remedy for a hot bearing is to add oil. Many times the new oil makes it difficult to determine the condition of the lubricant in the bearing at time of failure.

16

Ball and Roller Bearings

Ball and roller bearings have many desirable features. Their characteristics must be understood in order to make a fair comparison with a sleeve bearing.

Ball- and Roller-Bearing Construction

When two surfaces have motion with respect to one another, the friction is considerably greater when the two surfaces are in direct contact than when they are separated by balls or rollers. The bearings are composed essentially of balls or rollers interposed between two annular surfaces having relative motion. These latter parts are called "races."

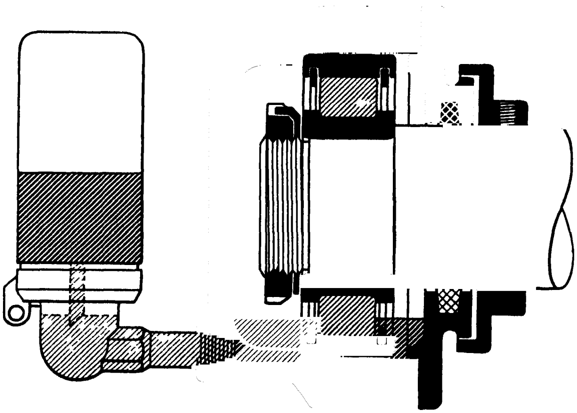


Fig. 1. Straight roller bearing.

Ball and roller bearings differ, as their names imply, in the shape of the rolling elements. The balls used in ball bearings are true spheres and have been ground and polished to extremely small tolerances. The bearing designs differ from one another only in the type of retainers, races, and housings chosen to adapt them for various services. Figures 1, 2, 3, and 4 illustrate the principal types.

The rolls for roller bearings consist of true cylinders, which are spaced by means of retainers or cages. These cylinders may be solid or in the form of a helix with the outside surface ground to a true cylinder.

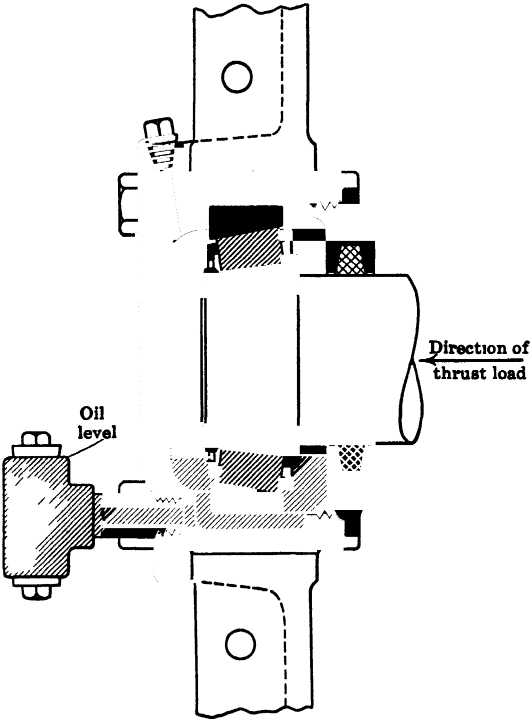


FIG. 2. Tapered roller bearing.

Needle- or quill-type roller bearings are small-diameter rollers running with or without cages. Lateral motion is prevented by end rings, and the cageless rollers have no fixed axis and hence may come into direct contact with each other during rotation. The use of smaller-diameter rollers, such as in needle- or quill-type bearings, permits a greater number of rollers and thereby greatly increases the number of inches of roller line contact.

Frequently needle bearings are run directly on a shaft to save room. Figure 5 will indicate that the shaft should be hardened if there is any

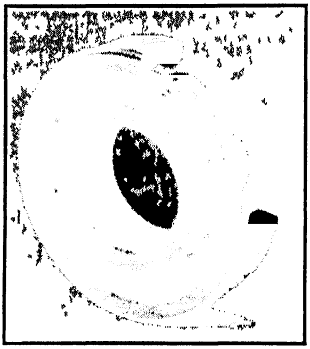


FIG. 3. Typical ball bearing.

appreciable load on the bearing. It is frequently cheaper to run the bearing on a hardened sleeve pressed on the shaft if there is room for the greater overall dimensions required.

Theoretically, the contact area between balls and their races is a point, and in roller bearings is a line. Because of deformation of the metal under pressure, the contact becomes a small area.

A tapered roller bearing is one in which the rolling element is a truncated cone. The races conform to the shape of the rollers. This design is especially adapted for conditions where a combination of radial and thrust loads are present.

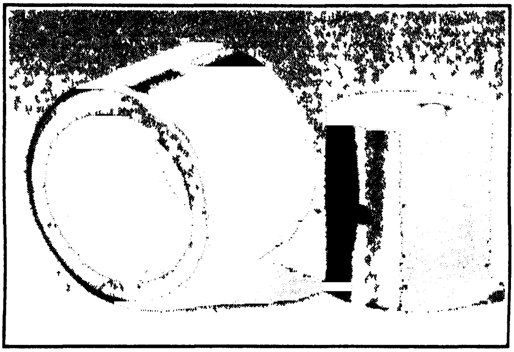


FIG. 4. The construction of a needle bearing. The shaft must be hardened when used as the inner race. See Fig. 5.

Bearing Mountings

The bearing mounting determines whether grease or oil may be used for the lubricant. Bearings located in internal parts of equipment are lubricated by the splash or circulating oiling systems.

Regardless of the method of mounting, certain requirements must be met in order to ensure successful bearing performance. Each bearing installation must be judged on its service requirements. Bearings are obtainable in a wide range of finishes and tolerances to meet service requirements. Mountings must conform to the same degree of accuracy as the bearing. As a general rule, because of the small internal clearance, not more than two bearings should be mounted on one shaft, as two points determine a straight line. For the same reason provisions must be made for expansion and contraction. Care must be exercised so that the inner race is not expanded or the outer race contracted in mounting so as to preload the bearing.

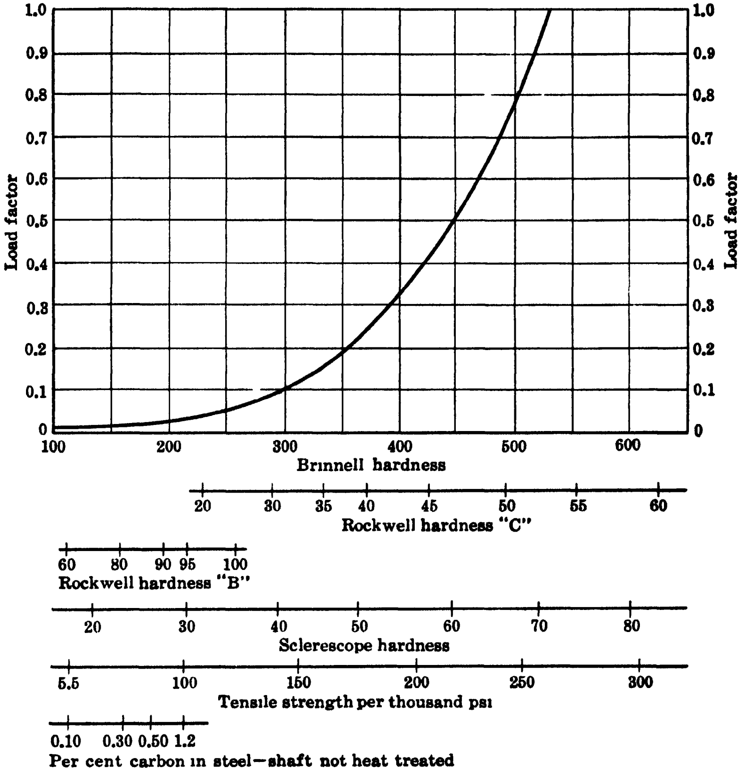


FIG. 5.

Means must be provided to exclude foreign matter, as the highly finished surfaces are easily destroyed. Bearings must be mounted with the proper tools, technique, and care to obtain optimum bearing performance.

Lubrication Requirements

The functions of a lubricant for bearings are:

1. To provide lubrication between the balls or rollers and their retainers, cages, and races.

2. To provide protection against corrosion.
3. To assist in forming a seal to prevent the entrance of dirt and solid matter into the housings or to remove foreign material by flushing.
4. To aid in dissipating frictional heat.

Suitable oils and greases meet the above requirements. In some bearing installations all the above requirements cannot be met. In an acid plant it is most important to provide protection against corrosion. For some equipment the best protection is obtained at the expense of some sacrifice in the lubricating characteristics of the lubricant. Then a compromise must be made in favor of the metal-protecting qualities of the lubricant.

The choice between oil and grease for lubricating bearings is governed largely by the design of the equipment. Only sufficient oil or grease is required to wet all surfaces. An excess of lubricant causes a temperature rise owing to the work done by the balls and rollers in displacing the lubricant.

When oil is used for lubrication, the most important characteristic to consider is the viscosity at the operating temperature. Bearings that are located on outdoor equipment or in unheated buildings should be lubricated with an oil of sufficiently low pour point to assure fluidity when starting. The selection of suitable lubricants for oil-lubricated bearings is not difficult because the requirements are similar to plain bearings in that slow-speed, heavy-duty bearings require relatively heavy oils and high-speed, light-duty bearings should be supplied with light oils. Bearings in warm locations or those exposed to high temperatures from an external source should be supplied with heavy oils to meet the thinning effect of heat upon oil.

Grease-lubricated antifriction bearings present a more difficult lubrication problem because grease is a combination of oil and soap, and both the kind of oil and the type of soap affect the properties of the grease. If the grease is not suitable for the operating conditions, separation of the oil and soap may occur with the result that the soap is deposited inside the bearing where it cakes, hardens, and interferes with proper operation. In the presence of moisture some greases emulsify, and leakage occurs. Other greases may channel excessively at high speed, so that the bearing is starved. Some greases do not remain stable, with the result that the oil bleeds excessively. The ideal grease would be one that would supply oil under all operating temperatures, speeds, loads, etc., at the exact rate of the oil evaporated or lost from the bearing. This ideal grease has not yet been found. The table gives some of the characteristics of the more common greases.

Grease (type base)	*Temp. Range in °F*[1]	*Water Resistant*	*Speed Range*
Sodium-calcium	0–200	No	Low to very high
Sodium	0–200	No	Low to very high
Calcium	0–120	Yes[2]	Low
Lithium (low-temp.)	−50–125	Yes	Low to high
Lithium (high-temp.)	0–200	Yes	Low to high
Barium	0–200	Yes[3]	Low to moderate
Strontium	0–200	Yes[3]	Low to moderate
Synthetic	−100–300	Yes, no	Low to moderate

[1] Most greases have a melting range from 200 to 500° F. Temperatures above those indicated in the table can be maintained only briefly unless greasing is to be very frequent.

[2] Water has a tendency to displace calcium soap greases from metal surfaces, and rusting is likely to occur.

[3] These greases appear to have a preferential wetting for metal over water, and afford excellent protection against rusting and corrosion from many chemicals.

Application of Lubricants

The application of a lubricant depends upon engineering principles and applies to all classes of operating equipment. A precision bearing in a grinder requires the same considerations as a precision bearing in any other piece of equipment.

The most common cause of lubrication difficulties with antifriction bearings is the application of too much lubricant at too frequent intervals. This is not so common on oil-lubricated bearings because either such bearings are equipped with an overflow to control the oil level or the oil is supplied in the form of a mist or spray. When balls or rollers dip into an oil bath and an automatic overflow is not provided, the oil level should be such that approximately half of the lowest ball or roller is submerged. When the oil level is higher than necessary the severe agitation of the excess oil results in unnecessary fluid frictional heat, which increases the bearing temperature and decreases the viscosity of the oil. In addition to causing a power loss, high oil levels tend to promote leakage.

When grease is applied by means of a grease gun, a common practice is to force in the grease until the housing is full. This practice results in a considerable churning effect on the excess grease. Not only does this raise the bearing temperature, but it tends to break down the structure of the grease.

The increase in operating temperature which follows the application of too much oil or grease sometimes influences the oiler or operator to add more lubricant and further aggravate the existing condition, even to the extent of blowing out the grease seals. When housings are fairly tight and a correct grade of grease is used, bearings require lubrication only every few years under normal operation. Equipment operating under adverse conditions of high temperature, wet locations, dirt, or corrosive fumes or liquids will require more frequent lubrication and inspection.

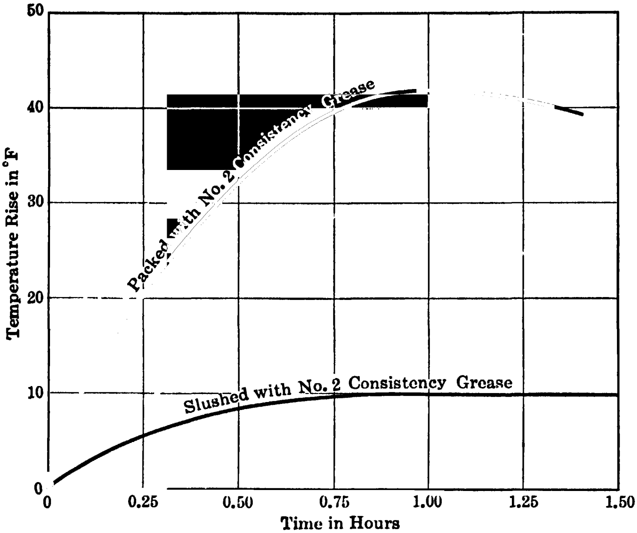


FIG. 6. Diagram showing the effect of packing grease into a single-row ball bearing operating at 1800 rpm.

The curves shown in Fig. 6 illustrate the effect of quantity upon the frictional temperature rise. This test was made with a medium-sized single-row ball bearing operating at 1800 rpm. The lower curve, which is marked "slushed with grease," shows the temperature rise when only sufficient grease to slush the surfaces was present. The other curve clearly shows the effect of additional quantities of grease on the temperature.

Figure 7 illustrates the effect of oil level on fluid frictional temperature rise. A single-row ball bearing operating at 3600 rpm was used, and the curve shows the effect of oil level on temperature when using S.A.E. 20 and S.A.E. 70 viscosity oils. The initial oil level was such that the lower ball was just submerged, and the level was decreased

⅛ inch for each successive run. Figures 6 and 7 clearly show the importance of keeping the oil level low or the quantity of grease used at the minimum.

An oil bath into which the balls or rollers dip is not generally satisfactory for very high-speed operations because the churning effect is so great that the temperature rise is excessive. Bearings operating at extremely high speeds should have oil applied in very small quantities, and this is generally accomplished by an oil mist created by the action of slingers which dip into an oil reservoir or by wick feeds which permit application at a very slow rate. The wick feed method, as applied to modern bearings, is really a miniature circulating system in which oil is drawn from the reservoir by the capillary action of the wicking, fed to the bearing, and is then drained back into the reservoir.

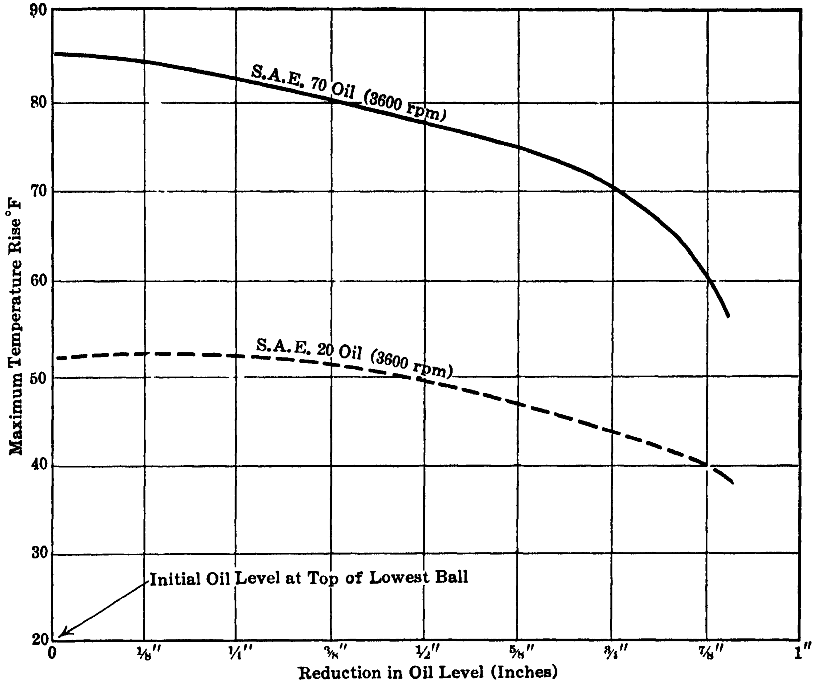


FIG. 7. Diagram showing the effect of a heavy oil and high oil levels in a bath-oiled ball bearing operating at 3600 rpm.

In some vertical installations operating at moderate speeds, a circulating system is employed in which spiral grooves or impellers on the shaft act as an oil pump and create enough pressure to carry oil over the top of the balls or rollers, from where it drains back into the reservoir.

Suggestions for Lubricating

Recommendations for assuring efficient lubrication of antifriction bearings are briefly summarized in the following paragraphs:

1. Do not fill grease-lubricated bearings more than one-third full of lubricant because any excess over this quantity results in unnecessary fluid friction and overheating. Never fill housings so full by means of a grease gun that the lubricant comes out of the bearing seals or vents. (Slow-speed, heavy-duty rolling-mill roll-neck bearings are exceptions.)
2. Do not put more oil in bath-lubricated bearings than is necessary to submerge half of the lowest balls or rollers.
3. Apply the lubricant only when necessary and in limited quantities.
4. Bearings should be cleaned, inspected, and relubricated as experience dictates.

Rusting of Antifriction Bearings

The effect of moisture on ball and roller bearings is an important factor in their operation because the highly polished steel parts are subject to rusting. When cold drafts strike a bearing housing, or when the equipment is shut down for a while, some condensation is likely to occur. Needless to say, rusting interferes with the operation of antifriction bearings by spoiling the surfaces. When this occurs, the bearings commence to chatter, or become noisy, and from there on destruction is more or less rapid.

Sodium soap greases and compounded oils afford better protection against rusting than lime soap greases and straight mineral oils. The former lubricants will pick up moisture and form an emulsion which greatly aids in preventing the formation of bare spots. For example, marine engine oils containing 10 per cent of rapeseed oil will provide an emulsion that effectively prevents corrosion.

Unfortunately sodium soap greases are too easily washed out when water actually enters the bearing, as it may, for example, in papermaking machines, etc. On the other hand, compounded oils cannot be used in circulating oiling systems because they emulsify and cause operating difficulties, nor can they be used if temperature is a factor, on account of their tendency to oxidize and sludge.

Solvent refined straight mineral turbine-grade oils do not afford good protection against rusting. They have a high demulsibility and separate quickly from water. Hence they tend to leave bare spots on highly polished steel surfaces. This condition is overcome to a large extent when the turbine oil has aged sufficiently to develop some organic acid which has protective qualities. Most turbine oils contain satisfactory rust inhibitors.

Bearing Failures

Bearings fail for lubrication or mechanical reasons. Bearing failures should be investigated to determine the cause, so that corrective measures can be taken to prevent a recurrence of the failure. Some of the more common reasons for failures are:

1. Lack of lubrication, which can usually be detected by excessive retainer wear.
2. Dirt and foreign material, which can be detected by excessive wear of all bearing parts.
3. Oxidation of the lubricant, causing varnishes and resins.
4. Soap deposits, which are generally hard, lumpy deposits caused by separation of the oil and soap in the grease.
5. Rust and corrosion, which can be observed upon inspection.
6. Overlubrication, which can be observed by broken seals, excessive lubricant leakage, and premature breakdown of the lubricant caused by excessive working and high temperature.
7. Use of the wrong type of lubricant.

Some of the more common types of mechanical failures are:

1. Normal failures based on "life expectancy." These curves are founded on a 10 per cent failure expectancy before the end of normal life. The failures may show up as split balls, broken retainers, spalled surfaces, etc.
2. Expanded inner race due to fit on shaft, which shows up as spalled inner race and entire spalling of outer race.
3. Deformed outer race caused by out of round bore, such as is likely to occur in split housings; this shows up as spalled spots in the outer race 180 degrees apart.
4. Excessive thrust, which can be observed by an excessive wear track on one side of the race in the direction of thrust. The most likely cause is lack of adequate provisions for expansion.
5. Spinning of the outer or inner race in the housing or on the shaft.

6. Friction oxidation or false brinnelling, which if found early can be detected by worn spots in the race spaced at the center distance of ball to ball or roller to roller. This failure is caused by limited motion of the bearing. It may occur because of vibration during shipment or storage, or during service where the design is such that the bearing oscillates only a few degrees.
7. Improper type of bearing or mounting for the service requirements.

Ball and roller bearings are precision equipment. They require quality lubricants and skilled installation and maintenance for maximum performance.

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Methods for Applying Lubricants

The method of applying the lubricant plays an important part in reducing wear and friction, and the various methods are discussed in the following paragraphs.

Hand Oiling

Hand oiling, or the application of oil at periodic intervals, is very inefficient because of the "feast and famine" condition. An excessive quantity of oil is usually applied at one time and the excess quickly runs out, leaving the bearing partially unoiled until the next application. This method is wasteful, irregular, unreliable, and necessitates the use of a heavier oil than would be required for a more efficient method of application.

Bottle Oilers

The bottle oiler consists of an inverted glass or plastic container with a metal spindle passing from the oil reservoir through a fairly

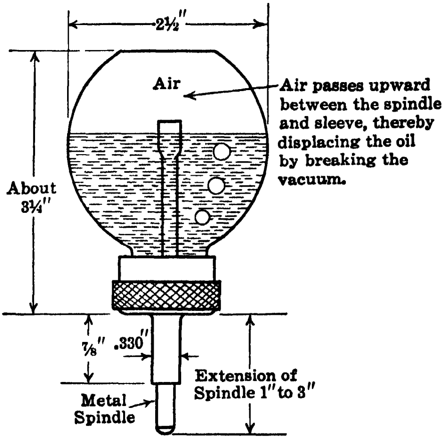

2½"
Air
Air passes upward between the spindle and sleeve, thereby displacing the oil by breaking the vacuum.
About 3¼"
⅞"
.330"
Metal Spindle
Extension of Spindle 1" to 3"

FIG. 1. Bottle oiler.

tight-fitting sleeve to the rotating journal. Figure 1 shows the construction and operation of a bottle oiler. The spindle rests on the journal, and the oil is caused to flow by several means, such as temperature changes or the vibration of the spindle on the shaft.

The oil feed is particularly sensitive to the clearance between the spindle and the sleeve. To increase the oil feed a very narrow flat spot may be filed on the spindle.

Bottle oilers are useful for low-speed, lightly loaded bearings where small quantities of oil are required. They should not require refilling oftener than 1 to 4 weeks. The principle is simple and of course superior to hand oiling. Bottle oilers are often made of glass, but plastic materials are safer.

Drop-Feed Cups

Drop-feed oilers are devices wherein the rate of oil flow may be controlled by means of a needle valve. They are used to a considerable extent and provide a fairly regular supply. However, the rate of oil flow varies with the temperature and viscosity of the oil and with the level of the oil in the container.

A rise in room temperature of 20° F cuts the viscosity of an oil nearly in half and doubles the rate of feed. Figure 2 shows the construction of a drop-feed cup. They are useful for intermittently operated equipment, as the feed can be started and stopped by a flip of the toggle lever. They are quite often constructed with a ball check when applied to such equipment as cylinders where the pressure periodically rises above atmospheric.

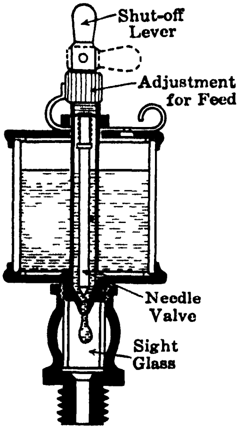


FIG. 2. Drop-feed oil cup with sight glass, showing needle valve and lever for adjusting the feed.

Wick-Feed Cups

Wick-feed cups consist of oil reservoirs or cups wherein one end of a wick dips into the oil and by capillary action drains the oil into the bearing. The rate of oil flow varies with the oil level in the cup, the temperature and viscosity of the oil, and the composition of the wick. The rate of oil feed may be regulated by increasing or decreasing the number of strands of wicking used.

The commonly used materials, graded for their ability to transfer oil, are: lamp wick, cotton, felt, wool, and combinations of these materials. Wool waste has a desirable rate of feed and is generally employed for the strands of wick feeds; cotton materials feed too rapidly. However, the choice depends very much on the rate of feed desired and the surrounding temperature. The higher the temperature of the oil in the cup the more rapid the flow.

Figure 3 shows the type of cup best adapted to wick-feed oiling. In this type of cup the level falls slowly and provides a reasonably uniform rate of flow. The cup shown in Fig. 4 is an unsatisfactory design because the level falls quickly and the rate of feed drops rapidly.

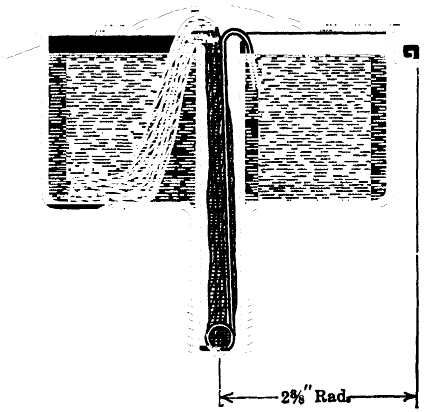


Fig. 3. Wick-feed oil cup.

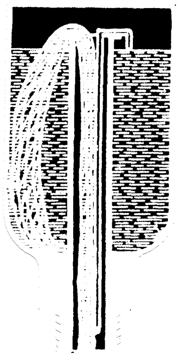


Fig. 4. Unsatisfactory design of wick-feed oil.

Wick-feed devices tend to feed oil at all times, even when the equipment is not running. To stop the feed it is generally necessary to lift the wicks out of the stand pipe, with the consequent risk that they may be forgotten upon starting up. Wicks become contaminated and tend to lose their feed rate. They therefore should in most cases be renewed on a definite schedule. Where an accurate feed is desired, it is advisable to observe the rate of oil flow before installing. These cups are useful where a reliable feed of oil is required and the operating time is relatively long compared to the down time.

Waste-Packed Bearings

Cotton materials, so superior in lifting and feeding capacity, are not suitable for waste-packed bearings because they glaze easily. Furthermore, cotton has very little elasticity, and positive contact with a revolving journal is easily destroyed by vibration and jarring. Wool waste is therefore employed in waste-packed journals, although other materials, such as combinations of wool waste and cotton, are also used.

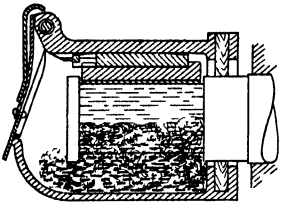


Fig. 5. Waste-packed car journal.

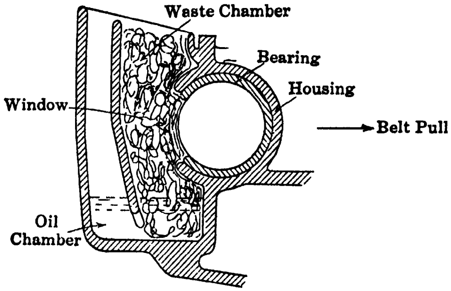


Fig. 6. Waste-packed armature bearing on railroad car.

Figure 5 shows the common design of a waste-packed car journal, and Fig. 6 shows the design of a car generator bearing.

The method of packing the waste has much to do with the proper operation of car journal bearings. The box must be filled uniformly along the length of the journal. In this connection, tests have demonstrated that, with hand packing, it is impossible to pack a bearing too tightly. When evenly adjusted by an experienced hand and properly lubricated, the waste may remain in a bearing for a period of 2 to 3 years without injury.

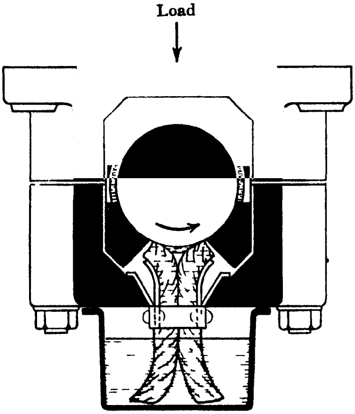


Fig. 7. Bottom-feed wick oiler for railway car journals. The journal pressure is against the upper half of the bearing.

There are many variations of waste-packed bearings; Fig. 7 shows one of these variations. In this design, stout wicks dip into the bath and supply oil to the revolving journal. Figure 8 shows another variation used extensively on small mechanisms. However, the principle of operation is the same in all applications of this method.

Felt pads are widely used for supplying oil to mechanisms where small quantities of oil are required.

Waste and felts should be changed at regular intervals, as they may glaze over or become charged with dirt.

These methods of lubrication provide boundary lubrication and are employed where it is difficult to retain oil or to provide an oil supply.

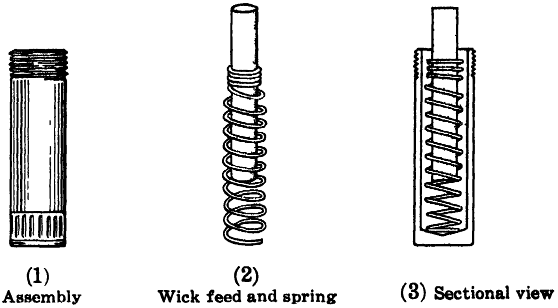


FIG. 8. Under-feed spring-loaded wick oiler.

Ring, Chain, and Collar Oiling

Ring-oiled bearings consist of a ring of large diameter which rides on top of the journal and dips into an oil reservoir below. The rotation of the journal causes the ring to rotate and carry oil from the reservoir up to the bearing. A ring oiler is really a miniature circulating system.

Figure 9 shows the principle employed in ring oiling, along with a constant-level device to maintain a uniform dip. In practice, the ring may be considered as a bearing of very large clearance which turns with the journal but at lower speed on account of slippage. An oil groove extending along the top half of the bearing acts as a collector and distributes the oil supply along the length of the journal. Hence the journal must be level or one side of the bearing may be unoiled.

When ring-oiled bearings are located in cold surroundings, the oil may congeal in the reservoir when the machine is at rest. The safest practice is to use an oil which has a pour point of about −20° F. In extreme cases it may be found advisable to use even lighter oils with much lower pour points.

Overheating is sometimes due to loads which may be toward one side, or even toward the top half, of the bearing. The top halves of ring-oiled bearings are slotted to permit the rings to rest on the journal and deliver oil to the top half. *Hence this method of lubrication is adapted only to downward load.* When the pull is shifted too far from this downward position, the bearing is liable to run warm, because the load commences to fall on the top half of the bearing, which is not designed for this purpose. The same is true when the load falls near the split halves of the bearing. The junction will disrupt the oil film unless the bearings are modified.

Collar- and chain-oiled bearings are similar in principle to ring-oiled bearings, except that, in chain oilers, a continuous chain is used in place of a ring. In collar oilers, a metal collar is fixed to the shaft. This collar dips into an oil reservoir and throws oil to the parts requiring lubrication.

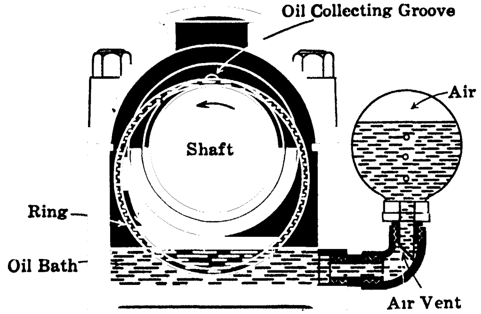


FIG. 9. Ring-oiled bearing with constant-level device attached. Note that the end of the shank in the constant-level device is beveled to permit prompt action when the level in the bearing housing drops slightly. It provides a vent by which air is admitted to break the vacuum and replace the oil supplied by the bottle.

Chains supply a copious amount of oil, but in damp locations where machines stand idle for some time failure often occurs because links in the chain rust. This prevents the chain from turning because it will not conform to the shaft. Under almost all conditions ring and chain oilers are reliable.

Bath Lubrication

This method is used where it is possible to submerge completely the rubbing surfaces in a bath of oil. However, the application is generally limited to vertical bearings, usually of the thrust or step type. Examples are found in hydraulic turbines of vertical design, wherein the thrust bearing runs submerged in a bath of oil, and in the textile industry where spindles run in an oiltight bolster or housing.

Splash Lubrication

As the name implies, this method of lubrication is produced by striking oil in a bath and causing it to splash into parts that require a continuous supply. This is a reliable means of lubricating many parts from one source. There are no parts of the oil system to fail; the only requirement is that the oil level and quality be maintained.

Circulating Oiling Systems

Circulating systems (see Figs. 10 and 11) provide a constant flow of oil to bearings and other parts requiring lubrication; the used oil drains into a reservoir and is recirculated. In a gravity circulating system the oil is pumped to a tank located above the parts requiring lubrication, and the oil flows down by gravity.

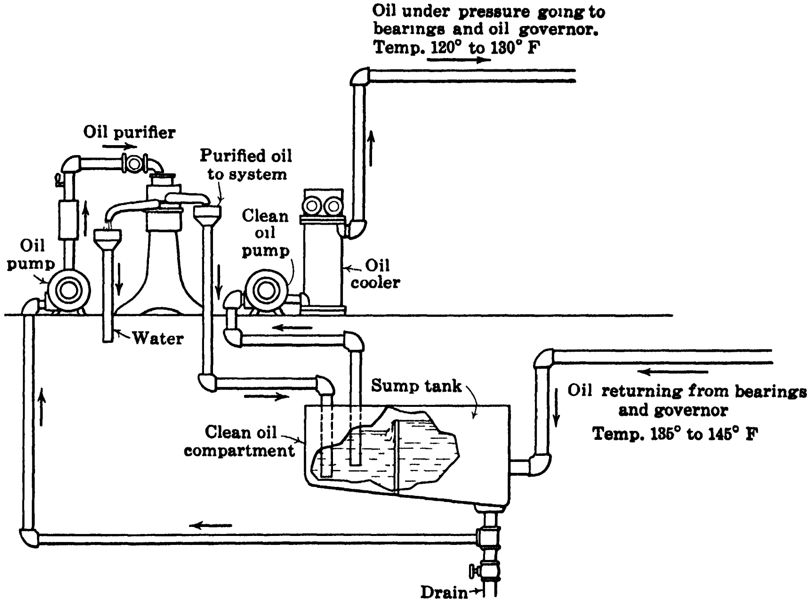

Oil under pressure going to bearings and oil governor. Temp. 120° to 130° F
Oil purifier
Purified oil to system
Clean oil pump
Oil pump
Oil cooler
Water
Sump tank
Oil returning from bearings and governor Temp. 135° to 145° F
Clean oil compartment
Drain

FIG. 10. Layout of circulating oil system, showing by-pass oil purifier.

These systems are very flexible, and coolers and oil purification systems may be added where necessary. For the most part circulating oil systems are employed where a large volume of oil is needed to cool as well as to lubricate the parts. These systems must be maintained like any other piece of mechanical equipment. In a pressure circulating system, oil is pumped under pressure directly to parts requiring lubrication, but in other respects the principle is similar to the gravity system.

A circulating system is the most efficient and reliable method of applying oil because it provides a copious flow of clean oil, and one system may be used to supply numerous bearings. Furthermore, heat is continuously conducted away from the bearings and is dissipated through the oil-cooling facilities. Obviously, for a method such as this, where the oil is in constant circulation, efforts should be made to minimize contamination, and facilities should be available for the removal of any impurities and oxidized oil to secure maximum life for the charge.

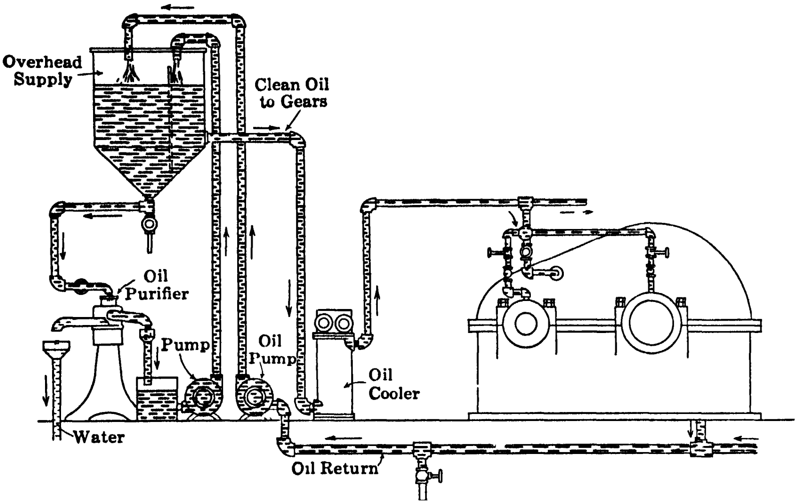


Fig. 11. Circulating oiling system applied to reduction gears. This particular method avoids pressure and excessive splashing at the meshing gear teeth where the oil wedge forms. Used oil drains from the gear case to a header, whence it is pumped to an overhead supply tank. Oil flows from the overhead tank by gravity through a cooler and returns to the gear set. A small quantity of oil flows from the overhead tank to a purifier, and the clean oil is returned by a second pump to the overhead supply tank.

The Mechanical Force-Feed Lubricator

This device consists of one or more small pumps, which are driven by small cams. Each pump is connected to an individual oil pipe, and the feed in each line may be regulated with considerable accuracy. For example, if the feed desired in one line is 2 drops a minute, and in another line 24 drops a minute, this setting will be maintained regardless of surrounding temperatures, type of oil in use, or any other factors.

Mechanical lubricators are employed for lubricating the cylinders of steam engines, internal-combustion engines, compressors, slow-moving journal bearings subjected to heavy pressures, and a great variety of moving parts on engines and machines where an accurate and positive oil supply is required. An incidental feature is that a delivery pressure of 5000 pounds or more to the square inch may be secured if necessary. (See Fig. 12.) Some lubricators are equipped with sight glasses filled with glycerine or glycerine and water; others drop by a sight window. This makes it possible to count the drops of oil.

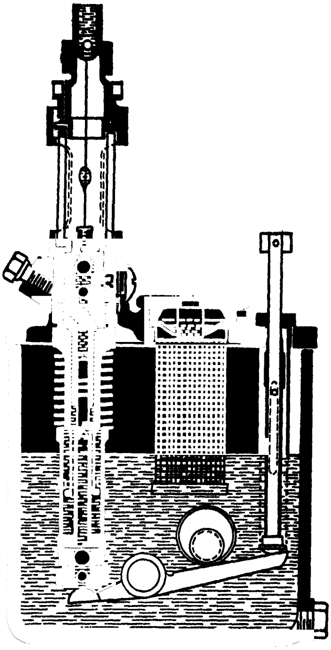


FIG. 12. Mechanical lubricator. A single-plunger pressure-feed lubricator, in which the sight glass is subjected to delivery pressure. This lubricator is operated by an eccentric which actuates a lever that engages a pump plunger. On the downward or suction stroke, oil is drawn through suction valves of the ball-and-seat type, and thence through the hollow plunger and into a pumping chamber. The pressure created on the upward or pressure stroke automatically closes the suction valves and forces oil from the pumping chamber to delivery valves (also of the ball-and-seat type), after which the oil emerges from a nozzle into the water chamber of a sight glass, and thence to an oil delivery pipe.

Hydrostatic Lubricators

Hydrostatic lubricators are employed for lubricating steam cylinders, either by the atomizer method or by direct application to the cylinder walls. However, this type of lubricator has been replaced largely by the mechanical force-feed lubricator, which provides an accurate control of the oil supply.

The operation of a hydrostatic lubricator depends upon the pressure obtained from a head of water. This pressure is produced by condensed steam and acts upon the oil in the reservoir to force it into the steam line, or steam chest. This type of lubricator is illustrated in Fig. 13.

The rate of oil feed for any one setting of the valves depends upon the head and temperature of the water in the condenser and upon the viscosity of the oil, which latter is influenced by room temperature. Because of these variables there is no control over the rate of oil feed. Hence the drops must be closely watched and adjusted by the operator, or they will vary in number to a considerable extent. The amount of oil supplied is also independent of the engine speed, and in a variable-speed engine the amount is not always proportional to the requirements. These inherent characteristics make it necessary to overfeed the oil to take care of possible requirements and variations in oil flow.

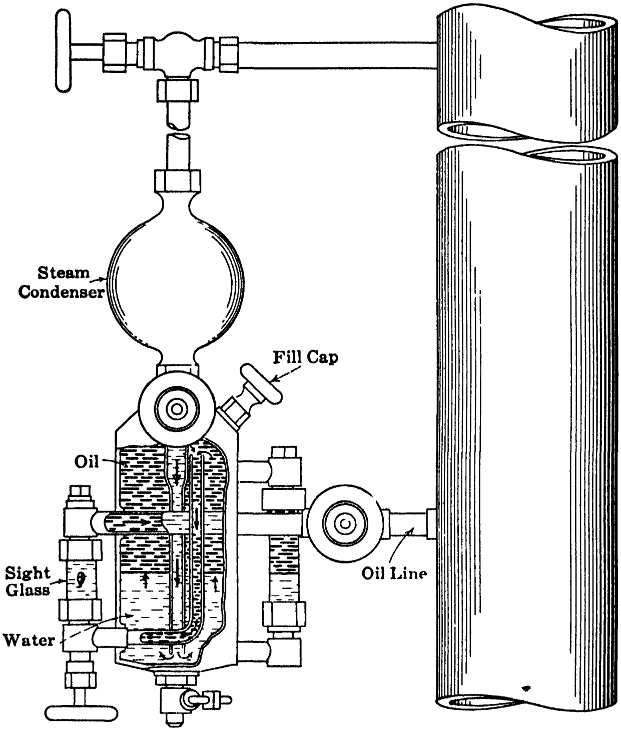


FIG. 13. Hydrostatic lubricator, applying oil into steam line. Notice that water displaces the oil. This water is produced in the steam condenser.

Automatic Lubrication Systems

There are many systems available for supplying oil or grease in metered amounts to many points on any cycle desired. Systems may vary mechanically, but all consist of the following essential parts: a pump, which builds up the required pressure to force the lubricant through the piping, swivels, hoses, etc., and metering valves. The pump may be hand operated, motor driven, or actuated by some part of the machine. The pump builds up pressure on a time cycle selected to meet the requirements of the machine. At the proper pressure the valves discharge a measured amount of lubricant. In some systems the amount of lubricant discharged by the valve is governed by the size of the valve selected. In other systems valves may be adjusted within limits, to vary the quantity delivered.

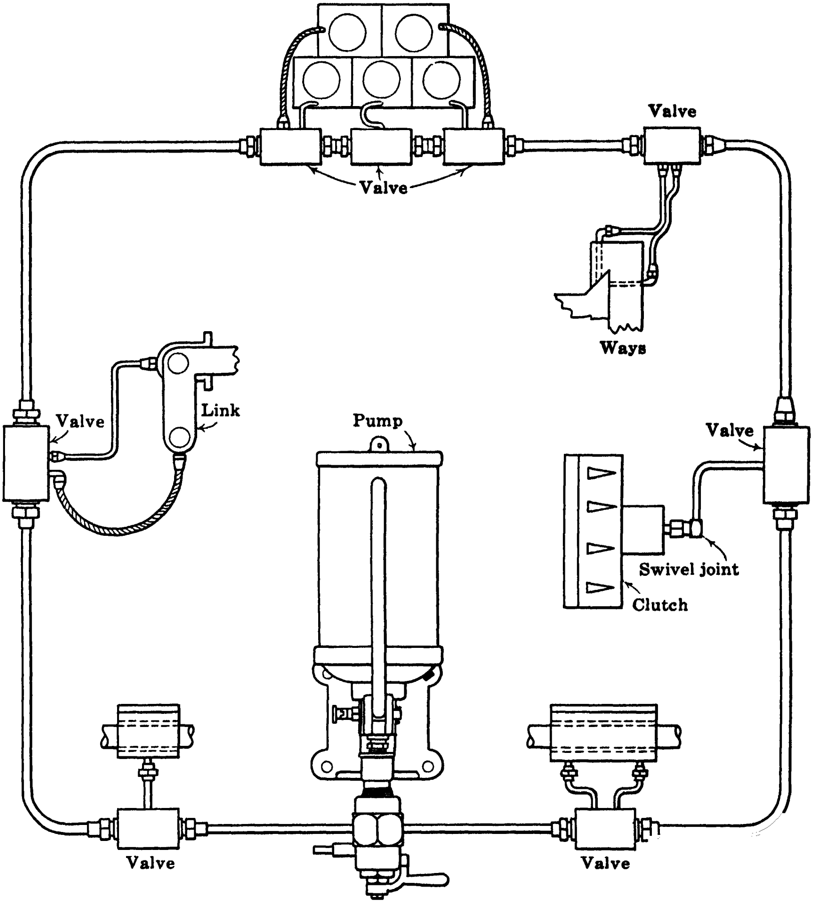


FIG. 14. Automatic lubrication system "schematic layout."

These systems afford great flexibility, as the time cycle may be changed easily and the valves offer a wide variety of feeds.

Some of the advantages of these systems are:

1. Known quantities of lubricants are supplied to all parts of the system at known intervals.
2. The lubricant is kept clean.

3. Physical hazards in lubricating the equipment are reduced.
4. Lubricant application time is reduced.
5. Down time for lubricating equipment is decreased.

It must not be assumed that an automatic system can be neglected and still function reliably. A few of the more common difficulties are:

1. Damaged pressure lines.
2. Soap deposits in grease-dispensing systems.

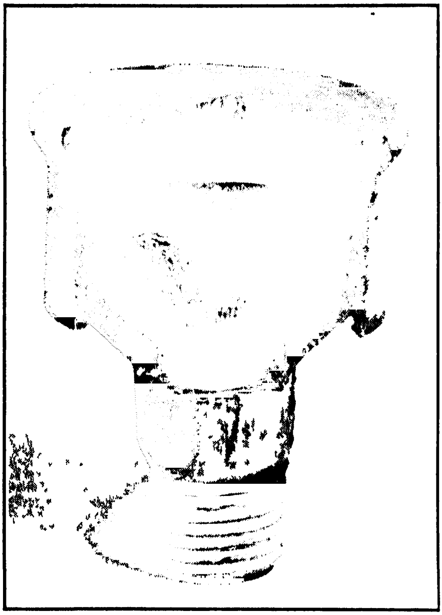


Fig. 15. Grease cup.

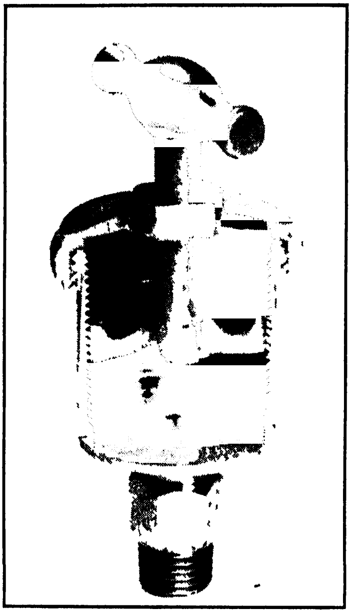


Fig. 16. Marine-type grease cup.

3. Damage of hoses, swivels, and other moving parts.
4. Occasional failure of a valve to operate.

Figure 14 shows a schematic layout of an automatic lubrication system. It will be noted that a wide variety of mechanisms can be serviced, and some thought must be given to the quantity of lubricant delivered to each moving part.

By far the commonest method of applying grease is through a high-pressure fitting by means of a grease gun.

Grease cups are useful where a small number of bearings require greasing or where a few bearings require a different lubricant from the one carried in the grease gun—as an example, the lubrication of a packing gland.

Figure 15 shows the conventional grease cup for applying soft greases. Figure 16 is the marine type for applying larger quantities and stiff greases.

Spring-loaded grease-dispensing devices that maintain the grease under pressure should be used with care, as most greases separate into soap and oil under pressure.

18

Oil Purification and Reclaiming

The filtration of lubricating oils is a much neglected subject. Actually 97 per cent of a used oil remains unchanged. Yet the remaining 3 per cent exerts such a profound influence that most used oils are discarded. This is something to ponder over.

In view of the wide variations in operating conditions to which oils are subjected, there is no universal method of oil purification suitable for all classes of service. The various methods of oil purification in commercial use are:

1. Settling.
2. Centrifuges.
3. Strainers.
4. Absorbent filters.
5. Adsorbent filters.
6. Distillation of volatile impurities.
7. Coagulation of impurities with chemicals.

Often two or more of the above methods are combined in a single filter.

Settling

Settling consists in allowing the used oil to remain in a tank, preferably a cone-shaped one, without agitation for a sufficient time to permit water and solid impurities to settle out. This method depends upon the difference in specific gravity of water, solid impurities, and oil. It is obvious that sludges and products of oil oxidation which have about the same specific gravity as the oil will not be readily removed. Therefore settling is primarily for the removal of water and heavy solid particles, and, because a period of several days is required for effective settling, this method is not suitable where the oil must be quickly purified for prompt return to service. When used oils are being allowed to settle, heat should never be applied continuously during the process because this sets up convection currents which tend to prevent impurities from settling out. However, it is desirable to heat the oil to facilitate settling, but the batch must be left to cool, and must remain undisturbed thereafter. The method is slow but effective.

Centrifuges

Centrifuges may be likened to settling tanks wherein the force of gravity is replaced by centrifugal force. By means of a whirling action which is capable of imparting a tremendous separating force, the materials heavier than oil may be separated with great rapidity.

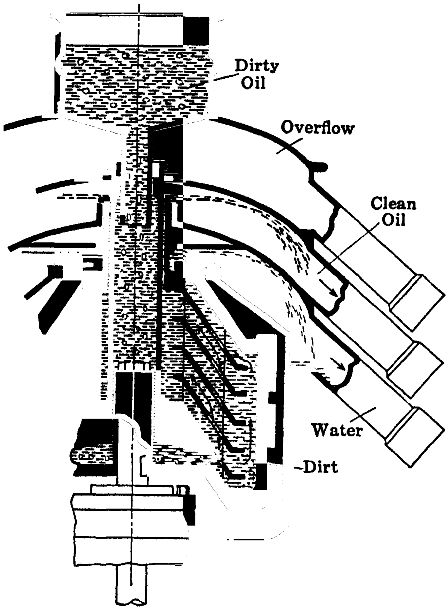
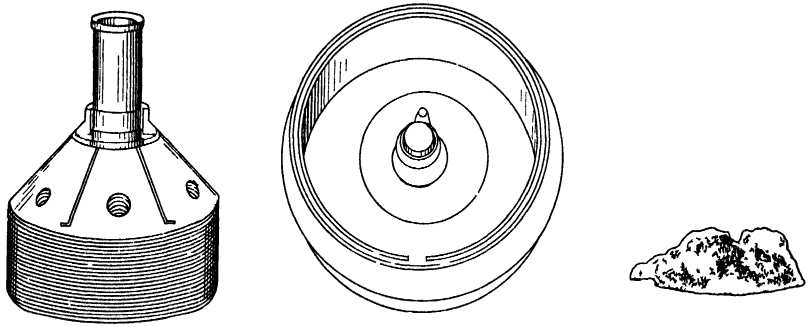


FIG. 1. Centrifuge. Used oil enters at the top of the centrifuge and passes downward through a hollow tube to the bottom of the purification bowl. The rotation of the vanes at high speed develops a centrifugal force that separates water and other heavier impurities from the lighter lubricating oil. The solid impurities are thrown to the outer circumference of the bowl. The water passes outward from the plates, upward to a discharge spout, and then to waste. The purified oil passes upward through holes in the plates to a clean oil discharge.

As shown in Fig. 1, the used oil enters a receiver at the top and passes down the hollow shaft to the bottom of the centrifuge. From this point the oil is distributed between revolving discs which have holes punched in them, as shown in Fig. 2. These holes allow the clean oil to move along the upper sides of the discs toward the center of the bowl, while water and impurities move along the lower sides toward the periphery of the bowl.

At the top of the centrifuge there is a variable-discharge ring which controls the balance between the weight of the water and the weight of the oil. Since oil is lighter than water, the purified oil is forced to discharge from the middle spout and water from the lower spout. The solid impurities remain on the side of the bowl, where they are thrown by centrifugal force and packed tight. They must be removed from time to time by dismantling the bowl.



Centrifuge discs. Centrifuge bowl. Impurities taken from bowl.

FIG. 2.

Owing to the fact that water is a solvent for the acidic materials produced by oil oxidation, the centrifuge should be primed with a liberal quantity of fresh water after centrifuging a batch of oil. This precaution will expel any contaminated water that remains in the device and will prevent corrosion of the discs.

As with all other types of filtering devices, centrifuges should be of liberal capacity. In fact, a good rule is to select a centrifuge of sufficient size to operate at half the rated capacity. By this procedure the filtering action will be found much more effective and satisfactory. As a general rule, the oil temperature should be about 120° to 160° F when centrifuging. The heavier the oil, the higher the temperature for best results.

Strainers

Strainers may consist of wire mesh, metal discs, cloth towels, or blotting paper. Strainers do not remove water or other liquid impurities. They will remove only the larger solid particles in used oil.

Strainers are often used in conjunction with other methods of oil purification, and the oil filter illustrated in Fig. 3 is a combination of settling and straining. The oil first passes through a wire mesh strainer and then to precipitation trays, where water is allowed to settle. After

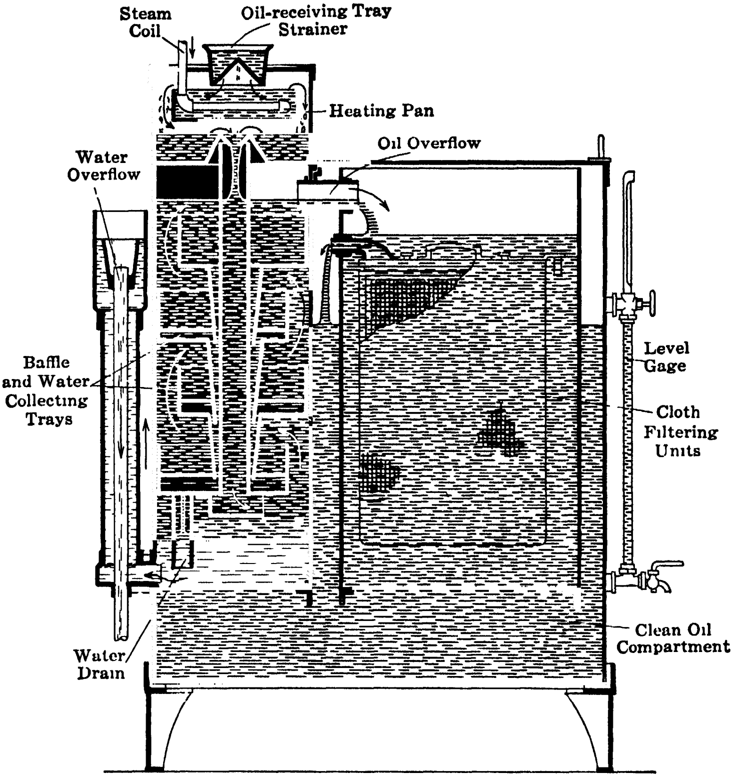


FIG. 3. Typical filter for purifying and reclaiming lubricating oils. Dirty oil enters through an oil receiving tray and is warmed in a heating pan, whence it passes through a vertical tube to the bottom of a precipitation chamber. The contaminated oil passes upward between several precipitation trays, leaving behind entrained water and some solid impurities. The partially purified oil enters a filtration compartment and passes through a series of filter frames which remove the remaining solid materials.

leaving the precipitation compartment the oil passes through cloth bags held on wire frames, where solid impurities are strained out.

Absorbent Filters

Absorbent filters consist of sponge, wood fiber, cotton waste, or similar materials. When such filters become saturated with impurities, the filter cartridge must be cleaned or replaced with a new one. This type of filter should be as large as possible. Experiments have proved that size is more important than special features in design. If the filter is too small for the job, special materials, etc., will not generally result in a satisfactory compromise.

Strainers and absorbent filters are always equipped with a relief valve or overflow which permits the oil to bypass the filter when the latter becomes clogged.

Adsorbent Filters

Adsorbent filters employ materials which do not absorb impurities as a sponge absorbs water. In this type of purifier, clay is employed as a filtering medium, as, for example, fuller's earth and diatomaceous earth.

These filters are highly effective in removing the very finest impurities. The method is also used in refineries. A small quantity of fuller's earth presents a vast area of contact surfaces to which impurities can adhere. With this type of filter, the smallest impurities may be removed from used oil.

Clay filtration cannot be employed effectively on oils that contain compounds or additives because clay will remove them to an appreciable extent. When the oil contains compounds, the surface of the clay particles sometimes becomes plugged and inoperative in a comparatively short period of time. This matter should be thoroughly investigated when a filter of this type is under consideration. However, when considered as a single medium, clay is probably the most thorough filtering material known. (See Chapter 4, "Refining Light Distillates and Lubricating Oil," under the subhead "Clay Filtration.")

Distillation

Distillation is employed in combination with purifiers to remove the fuel dilution from used crankcase oils. The process generally consists in heating the oil to about 300° F. This process will not remove all the dilution, particularly the heavy ends of No. 2 fuel oil, but an appreciable percentage may be driven off.

The effect of the undistilled portion may be overcome to some extent by adding a small percentage of new oil that is one grade heavier. As a general rule this procedure is necessary only when dilution is excessive.

Coagulation

Coagulation of impurities and acidic compounds by means of chemicals is an effective method for treating used oils from internal-combustion engine crankcases. By the addition of chemicals such as soda ash, trisodium phosphate, or sodium silicate, generally in solution with water, the impurities are coagulated by the chemicals and subsequently removed by settling, filtering, or centrifuging.

Many of the commercial automotive oil reclaimers on the market utilize chemicals for purifying the oil, and the complete units sold for this purpose are equipped with heating facilities for removing gasoline, a tank or compartment for treating with the chemicals, and a filter compartment, or centrifuge, to remove the coagulated impurities and the chemical solutions. Most of these oil reclaimers are fairly efficient when properly operated, but the sizes and types commercially available for small operators will not purify the oil so that it becomes as good as new oil. This can be done, of course; but the equipment necessary is so costly and elaborate that it is beyond the means of individual operators who purify their own used oils.

As an example of reclaiming by coagulation in a small device, the actual analyses shown in the table may be compared.

	New Oil	*Reclaimed Oil*	*Used Oil*
Gravity	29.0	28.4	27.7
Flash, °F	445	420	360
Fire, °F	505	490	410
Viscosity at 100° F	520	560	540
Viscosity at 210° F	67	70	69
Color	5½	8	Black
Carbon residue (%)	0.75	0.85	1.42
Ash (%)	None	0.01	0.10
Moisture (%)	None	None	Trace
Sediment (%)	None	0.01	0.18
Gasoline dilution (%)	None	Trace	2.0
Neutralization no.	0.10	0.14	0.92

A comparison of the oils in the test shows that the reclaiming process materially improved the used oil, but the reclaimed oil is not comparable with the new oil. The viscosity of the reclaimed oil is higher than that of the used oil because the gasoline dilution was substantially removed. However, the higher viscosity of the reclaimed oil in comparison with the new oil shows that only part of the oxidized oil was removed in the purification process.

Any reclaiming method that incorporates chemicals should be investigated carefully to see that the oil is not over-refined, and, if additives are present, that their effectiveness is not impaired.

It must be remembered that in any circulating oil system it is not economically feasible to install oil purification and reclaiming equipment that will be large enough to take care of any unusual condition, such as a severe water leak in a water cooler.

19

Machine Storage and Shipment

The protection of machinery in transit or storage is a function which should prove interesting to the lubrication engineer. Many failures attributed to lubrication have their origin before the equipment is put into service.

The most common is the rusting of ferrous materials. Other causes of trouble are brinelling of ball and roller bearings, entrance of dirt into machine parts, and the use of rust-preventive and cleaning compounds which are not compatible with the materials of construction or the lubricant.

Finished surfaces are most susceptible to rusting. This complicates the problem of protection and detection, as many times these surfaces are inaccessible. Inspection of the exposed surfaces may be very misleading.

The value of the equipment and the conditions of storage and shipping govern the procedures required to give complete protection.

Rusting

There are four properties which a rust-preventive material should have:

1. The material should offer good protection against rust and corrosion.
2. The material should be easy to apply.
3. The material should be easy to remove.
4. For some uses the material should have an attractive appearance.

The rust-preventive compounds fall into approximately three classes:

1. Rust preventive with mineral oil as the vehicle. This type of material is recommended for inside storage and for internal protection of inaccessible parts, such as gear cases and engines. Where these compounds are used it should be necessary only to drain and fill with

the proper lubricant. In general, the more viscous the material, the more lasting the rust protection. These types of products may be applied by spraying, brushing, dipping, or by filling oil reservoirs. The life expectancy is generally 1 to 3 years. Most of these products require dry surfaces for application, while some products will displace small traces of water, such as fingerprints.

2. Rust preventives which are plastic materials. These plastics may dry hard to prevent abrasion or may remain waxy to prevent displacement by water. The harder the film, the more difficult the removal and also the better the protection. Plastics are often pigmented to aid in obtaining complete coverage. Usually the materials are heated to 140 to 160° F for application. The materials are applied by dip, brush, or swab. They are used in outside service and for long-term and severe inside storage.

3. Class 1 and 2 products may be diluted with a petroleum solvent, generally with a flash point above 100° F for safety. When the solvent evaporates they form a thin film, and offer poorer protection than the undiluted compounds. They are used for short-term favorable storage and shipping conditions. They are sometimes justified because of their low over-all cost and because they can be applied at low temperatures.

False Brinelling, or Friction Oxidation

In Chapter 16 false brinelling was described. Bearings are frequently damaged in storage or shipment by this process. Lubricants or rust preventives are of little help in preventing this type of damage.

False brinelling damage can be prevented by storing equipment in areas free from vibration. In expensive and important machinery it might be well to remove the bearings during either storage or shipment. Every three years, equipment that is stored should be turned over and rust proofed.

Dirt

Much of the dirt found in the air is of an abrasive nature, which is ruinous to precision equipment and damages the most rugged equipment if it finds its way into the working parts. The most effective way of excluding dirt is to provide a suitable barrier between the air and the equipment. The type of barrier is dependent upon storage conditions, the size of the equipment, and the strength requirements.

Papers, plastics, wood, and metal are all used to protect equipment. Dirt, like moisture, has a way of migrating through any small opening.

Equipment worth protecting should receive nothing less than first-class care.

Economics governs the degree of protection that will be afforded any piece of equipment. A battleship laid up for storage may receive a million dollars' worth of protection. In addition, a complete inspection program is set up to ensure the effectiveness of the program. In contrast to this, a power shovel might receive 25 dollars' worth of protection when put up for the winter.

The procedures outlined in this chapter cover the minimum requirements for the average industrial storage and shipping problems. Machine storage, shipping, and packaging are highly specialized subjects. An extensive program should be undertaken only after suitable study.

20

Steam Engines

Application of the Oil

For the great majority of slide, piston, and corliss valve types of engines operating on wet steam and not equipped with steam jackets the best way to apply cylinder oil is by means of an atomizer called a "quill" in the steam line. This device is illustrated in Fig. 1. The purpose is to utilize the flow of steam to break up the oil into a fine mist, thereby assuring maximum oil distribution over the internal moving parts.

The best atomization is secured under high rates of steam flow, such as from half to full throttle operation. Relatively poor oil dispersion is obtained under idling conditions with low steam flow.

Wherever possible, the atomizer should be located between the throttle valve and the steam chest; otherwise the valve may have a tendency to act as a baffle and partially smother the atomizing effect. For the same reason the atomizer should not be located ahead of a bend in the steam line if this can be avoided, and never ahead of a water separator.

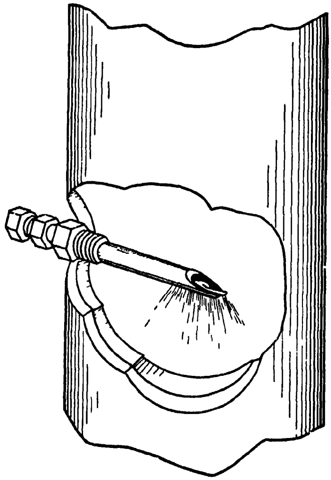


FIG. 1. Oil atomizer in steam line. The oil is supplied by a mechanical force-feed lubricator.

Engines equipped with steam jackets are best lubricated by direct oil applications to the valves and cylinders for the reason that steam jackets definitely tend to act as baffles and destroy the purpose of an atomizer. The number of oil-feed pipes will depend upon the design and size of the engine. In uniflow engines, piston valve engines, and large corliss valve engines, each cylinder may require two or more individual oil leads to strategic points. However, in all individual-point applications the location of an atomizer in the steam line will generally be found advantageous in lubricating the steam admission valves and throttle valve packing.

When engines operate on superheated steam, the best method of application is by means of individual oil leads directed to the high-pressure valves and cylinder walls. The number of leads depends upon the size of the cylinder and other design considerations, but, if the engine is large and the superheat high, as, for example, 100° or more, the most advantageous practice is to have at least two leads to each cylinder. In fact, large cylinders and high-superheat conditions sometimes present a difficult problem in lubrication which can only be overcome by applying the oil at several points around the circumference of the cylinder. This practice is based on the obvious advantage of delivering a small quantity of oil at several points rather than a large supply at one or two points, and allowing the thin hot oil to work around the cylinder. The addition of an atomizer in the steam line will generally be found beneficial, but the feed at this point should be sparse to avoid carbonizing troubles. (See Fig. 2.)

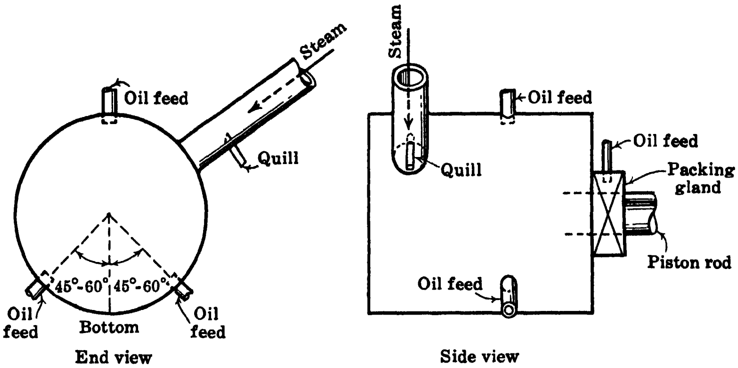


FIG. 2. Application of lubricant for steam engine operating on superheated steam.

If this adjustment fails to effect a cure the atomizer may be equipped with a push rod or taken out and cleaned at intervals determined by the rate of carbon deposits. Carbonizing of atomizers is more of an annoyance than a problem and is generally confined to isolated cases.

Types of Cylinder Oils

There are two principal types of steam cylinder oil—filtered and unfiltered—and either type may be compounded with 3 to 12 per cent of tallow or lard oil. Those oils which have been filtered are termed bright stocks. They have been filtered through fuller's earth, which reduces the carbon content, lightens the color, and enhances the ability of the oil to separate from water. Hence, the use of a filtered cylinder oil is advantageous when separation from the condensate is important. Where engines are operating on dirty steam, a filtered cylinder oil, compounded or uncompounded, will improve conditions by reducing the baked deposits which tend to collect on the internal moving parts. These deposits are accumulations of impurities and cylinder oil. The latter acts as a binder to make a hard paste which eventually bakes onto the internal parts.

Carbonizing of Atomizers and Oil Leads

This problem arises when cylinder oil bakes into a hard deposit in the atomizer tube. Sometimes the difficulty may be eliminated by adjusting the tube to slope downward for the reason that this baking effect has a tendency to occur on surplus oil that remains in the pipe after the steam has been shut off. By sloping the atomizer 2 or 3 degrees in a downward direction the tube will drain easily and the trouble will thus be avoided.

The specifications on p. 189 show the physical characteristics of filtered and unfiltered straight mineral cylinder oils. The viscosities in each example are the same to simplify the comparison. The majority of engines employ unfiltered cylinder oils because of their economy in price per gallon and because no particular operating condition or problem is present to warrant the use of a filtered oil.

Oil-Feed Rates: Wet and Superheated Steam

The rate of oil feed to a particular engine is by no means a cut and dried proposition for the reason that much depends upon the condition of the piston rings, engine speed, size, condition of the steam, and similar factors. Furthermore, for engines exhausting into the atmosphere a more liberal feed may be supplied than for a similar engine exhausting into a condenser and employing the condensate for boiler-feed water. In the latter case separation of the oil from the water is an important factor, and a high rate of oil feed complicates the problem.

The best way to determine the most advantageous oil-feed rate is to remove the cylinder head and test the cylinder walls with cigarette paper. This method will show whether an oil film is present during operation of the engine. The oil-feed rates shown in the table and Fig. 3 are based on average operation and may be used as a guide in determining the most advantageous rate for a particular unit.

OIL-FEED RATE GUIDES FOR WET AND SUPERHEATED STEAM *

Diameter of Cylinder in Inches	*Pints per 24 Hours Based on U. S. Gallons*
6 to 12	3.6 to 4.8
12 to 24	3.6 to 7.2
24 to 36	4.8 to 9.6
Above 36	7.2 to 12.0

* Engines operating on partial loads generally require an increased rate of feed because condensation increases on the cylinder walls. Under these circumstances, auxiliary oil feeds to cylinders and valves are helpful. (See Fig. 2.)

EXAMPLES OF STEAM CYLINDER OIL SPECIFICATIONS *

Crude	*Gravity A.P.I.*	*Flash, °F*	*Fire, °F*	*Viscosity Saybolt at 210° F*	*Pour Point, °F*	*Color A.S.T.M.*	*Carbon Residue, Per Cent by Weight*
				Unfiltered Cylinder Oils			
Pennsylvania	27	560	625	155	45	Dark green	2.50
Mid-Continent	26	540	610	155	20	Black green	2.00
				Filtered Cylinder Oils			
Pennsylvania	27	560	625	155	35	8	1.80
Mid-Continent	26	540	610	155	10	7	0.75

* In the above examples all tests were carried out under the methods of the American Society for Testing Materials.

Multicylinder Engines

Multicylinder compounded engines are not generally considered as separate problems in lubrication. If the cylinder oil is properly selected for the high-pressure cylinder it will be thoroughly atomized, thinned, and mixed with the steam when it reaches the succeeding cylinders. Occasionally, it may be found advantageous to compromise a little by favoring the low-pressure cylinder or cylinders with a lighter oil and more compounding than would be considered correct for the high-pressure cylinder alone. However, steam pressure behind the piston rings presses them against the cylinder walls, an effect which is more pronounced in the high-pressure cylinder than in the low-pressure. Hence, any compromise must not be toward an oil too light in body when favoring the low-pressure cylinders.

Where the engine design is such that steam passages from succeeding cylinders may baffle the oil, the low-pressure cylinders generally require the aid of extra oil leads, particularly if they are more than 36 inches in diameter.

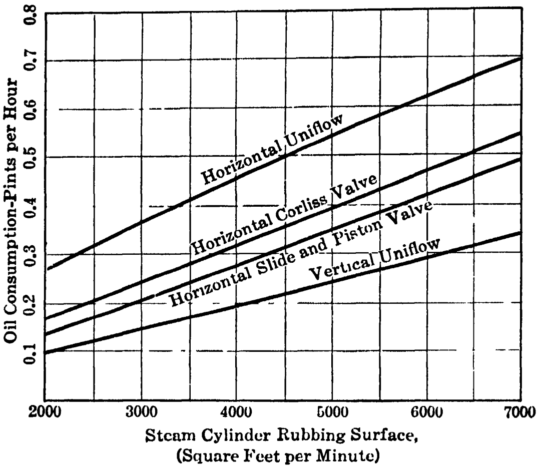


FIG. 3. This chart is based on the case histories of more than 1000 steam engines. No account was taken of steam conditions, type of oil used, or other details. The cylinder feed rates may be accepted as average.

Feeds should not be excessive, if for no other reason than that all the oil is lost once it passes through the cylinder.

Inspection of Piston Rings and Valves

With superheated steam, the life of piston rings is generally shorter than with wet steam for the reason that oil films are thinner and weaker owing to the higher operating temperatures. Hence the piston rings should be examined every 1 to 5 years, depending on the steam conditions. At the time of examination the sharp edges should be chamfered about $\frac{1}{16}$ to $\frac{1}{8}$ inch if the rings are found suitable for continued service. This precaution will materially assist the maintenance of the oil film on the cylinder wall.

The side clearance between the ring and its groove in the piston should be carefully maintained, since excessive clearance causes pound-ing, accelerates wear, and permits rocking of the ring with resultant high wear.

In marine practice, particularly where no cylinder oil is used, the rings should be examined at least once a year.

Valves, particularly those of the poppet type, should be examined and cleaned periodically. In some high-superheat operations carbon may form on the valves very rapidly, particularly on the exhaust valves.

Valve and Cylinder Lubrication

Wet Steam

When steam leaves the boiler without superheat it will contain some free water upon reaching the engine throttle valve. Under average conditions wet steam generated at 200 pounds or less will contain 5 to 15 per cent suspended moisture when it reaches the engine throttle valve. When engines are located at some distance from the boilers, or when steam lines are not properly insulated, the moisture content will be correspondingly higher.

Very Wet Steam

In steam-engine operation the factors which have the greatest influence on steam conditions are steam pressure, load, cutoff, cylinder size, piston speed, and length of steam pipe. When engines operate on partial load the effect of condensation on cylinder walls and valves is generally pronounced. Early cutoff has a similar effect.

For engines operating on wet steam and pressures below 150 pounds per square inch, a light cylinder oil of about 120 to 150 seconds Saybolt viscosity at 210° F should be used. Such lubricants will flow readily over the cylinder wall and valve surfaces, and if 10 per cent of compounding in the form of tallow or lard oil is incorporated in the cylinder oil it will provide a strong emulsion that will adhere to the wet surfaces and resist the washing action of moisture. Under the conditions outlined, 10 per cent of compounding will often cut the necessary oil-feed rate to half that of a straight mineral oil.

Normally Wet Steam

Steam engines operating continuously at full load and supplied with steam that does not contain more than 5 to 10 per cent of moisture at the throttle valve are seldom difficult to lubricate. Steam velocities are sufficiently high to atomize the oil thoroughly, and condensation is not generally excessive.

Generally, the cylinder oil should have an approximate Saybolt viscosity of 130 to 180 seconds at 210° F and 5 to 10 per cent of compounding for pressures below 200 pounds. The higher the pressure, the heavier the oil and, as a general rule, the less compounding required to maintain a satisfactory emulsion on the cylinder walls.

For example, under normal conditions, steam generated at 200 pounds near the engine will not contain much moisture at the throttle valve. The pressure may show a slight drop, but the moisture content will probably be about 5 per cent. Hence, with ample steam velocity to break up the oil and a temperature of approximately 380° F, a cylinder oil having a Saybolt viscosity of 150 to 180 seconds at 210° F and 5 per cent of compounding would be a normal recommendation.

The addition of compounding in the form of tallow or lard oil will maintain a good emulsion by mixing with the moisture, thereby increasing the tenacity of the oil film and retarding the washing-out action. With efficient oil-extracting equipment the compounded oil may be taken out of the condensate without difficulty. Otherwise a straight mineral oil should be used. However, the benefit of this latter practice is often doubtful because the oil-feed rate must be increased to secure satisfactory lubrication.

VISCOSITY AND COMPOUND GUIDE FOR WET STEAM AND TEMPERATURES BELOW 450° F *

Pressure at Throttle Valve (psi)	*Saybolt Viscosity at 210° F*	*Per Cent Compound Tallow or Lard Oil*
Under 150	100 to 160	10 to 12
150 to 200	140 to 180	5 to 10
200 to 500	160 to 225	5 to 8
500 to 1000	180 to 300	5 to none

* When condensate is returned to the boilers and the oil extraction equipment is not capable of removing a compounded oil, use an oil without compounding to secure maximum separation of oil from water. Follow the chart for steam pressures and approximate viscosities. For large horizontal engines, favor the higher-limit viscosities.

Superheated Steam

To explain engine cylinder lubrication under conditions of superheated steam, it is helpful to draw conclusions from the behavior of lubricating oils in the cylinders of other types of engines. By following this procedure, factors which are often difficult to understand in engines operating on superheated steam can be logically assumed through these comparisons.

For example, in the cylinders of any internal-combustion engine, over-all temperatures of the burning and expanding gases are much higher than in steam engines. In Diesel engines the maximum temperature of combustion is approximately 3000° to 3500° F, which is sufficient to vaporize and destroy the heaviest oils made, while that of the exhaust is approximately 1500° F just before the opening of the valve or port. Yet there is very little difficulty in lubricating the cylinders of average internal-combustion engines with comparatively light oils. In fact, engines of this type never require lubricants comparable in viscosity to steam cylinder oils.

In the cylinders of most gasoline and Diesel engines, the lubricating oil is spread over a water-cooled surface. Hence, an oil film of microscopic thickness survives these high temperatures, because it is maintained on a comparatively cool surface. Experiments show that the average surface temperature on the cylinder walls of internal-combustion engines is about 300° to 350° F. Even if the average temperature is 350° F it is still comparatively cool because the lubricating oil is being replenished with each stroke of the piston. Now consider the steam engine.

Steam Cylinder Wall Temperatures

Operation of a steam engine cylinder is just the opposite of that of an internal-combustion engine. Instead of the cylinder walls being cooled, they are insulated against heat losses to reduce condensation and are very often equipped with steam jackets to maintain the highest possible operating temperature on the internal surfaces. Hence, steam cylinder walls are maintained at higher operating temperatures than the walls of internal-combustion engines. For wet-steam operation, these temperatures can be handled with comparative ease by oils of the type known collectively as light- and medium-viscosity cylinder stocks.

For example, when the steam pressure at the throttle valve is 250 psi, the steam temperature will be about 405° F and an average cylinder wall temperature under these conditions will be about 350° F, depending upon the type of insulation around the cylinder (asbestos or steam jacket). This range is well within the working temperature range of cylinder stocks.

Significance of Viscosity and Flash Point

Nature has placed a limit on the temperatures which the heaviest-bodied cylinder oils can withstand. At temperatures above 600° F the heaviest steam cylinder oils will commence to "crack" and give off volatile vapors but a good average-grade oil will give off very little vapor; nevertheless at these temperatures the flash point has been reached or passed for most cylinder stocks. There are cylinder stocks of very heavy body which have flash points higher than 700° F, but their carbon-forming tendencies are correspondingly high, and for this reason their use for high-superheat conditions is controversial.

For use with superheated steam the steam cylinder oil should have a flash point of not less than 540° F for the lighter grades and not below 600° F for the heavier grades. Since the fire point of cylinder oils is about 75° F above the flash point, the corresponding fire points would be about 615° F and 675° F, respectively.

However, flash and fire points are only a theoretical guide to the possible behavior of oil films on hot cylinder walls. These oil films are only about 1/1000 of an inch in thickness and in that position are extremely vulnerable to disintegration from heat. Furthermore, at high temperatures the heaviest cylinder oils tend to fry up into little spheres.

Furthermore, all lubricating oils tend to approach a common viscosity as the temperature rises. For example, when a cylinder oil of medium viscosity is heated to 450° F it is not much thinner than a heavy cylinder oil at the same temperature. The comparisons shown in the following table demonstrate this feature.

	Crude	*Grade*	*Viscosity at 100° F*	*Viscosity at 210° F*	*Viscosity at 450° F*	*Carbon Content by Weight*
A	Pennsylvania	Unfiltered	9000	300	40	4.5%
B	Pennsylvania	Unfiltered	2400	150	37.5	2.50%
C	Pennsylvania	Filtered	2400	150	37.5	1.80%

Notice how the viscosity of the heavy oil A approaches the viscosity of the lighter oil B as the temperature rises. At 450° F the oils have reached viscosities of 40 and 37.5 seconds, respectively, and from this point on, the viscosities remain comparatively constant until distillation temperatures are reached. Notice also the lower carbon content in oil C, which has been filtered through fuller's earth. As stated previously, this latter type gives maximum separation from water.

The oil entering a steam cylinder is hot before it reaches the internal moving parts because it travels slowly, drop by drop, through the feed line. Upon reaching the hot cylinder, or steam pipe, it is thinned down to an appreciable extent. If the oil travels through a steam jacket before reaching the cylinder the thinning effect is more pronounced. From this it will be seen that the property of a steam cylinder oil is very much changed after leaving the lubricator. The oil film on a cylinder wall is a light-bodied, tenacious fluid, quite different from its viscous and original state in the shipping drum.

Filtered cylinder oils having Saybolt viscosities above 200 seconds at 210° F are not widely available, and their performance data are therefore limited. Most engines operating on superheated steam are lubricated by heavy unfiltered oils, or preferably by blends of the lighter filtered stocks with heavier unfiltered stocks. However, with high-temperature steam the most important consideration is to provide a sufficient number of oil leads around the cylinder and thereby maintain the oil film with a small feed of comparatively cool oil at each point.

Effect of High Temperatures on Compounded Cylinder Oils

Whenever moisture is present in engine cylinders, tallow or lard oil will materially improve lubrication. These materials combine with moisture to form a tenacious emulsion, and this effect cuts down the rate of feed that would otherwise be required. Owing to the washing effect of moisture, straight mineral oils are easily washed out of cylinders and a higher rate of feed is required to maintain the oil film.

However, little or no tallow or lard oil is generally advisable when the original temperature of the steam is raised more than 100° F by means of a superheater. Emulsifying materials of this type tend to increase the rate of the deposit formations at temperatures above 500° F. However, for intermittent operation, early cutoff, long steam pipes, and similar operating factors, a small amount of compound is sometimes advantageous to produce an emulsion with the resulting moisture. For example, when hot steam strikes the comparatively cool steam chest and cylinder walls of an engine that is continually starting and stopping, there may be sufficient condensation to warrant adding 5 per cent of compounding, regardless of superheat conditions.

Steam that contains 50° to 100° F of superheat should not present a problem in lubrication because a temperature drop occurs between the boiler room and engine throttle valve. Upon expanding a short distance in the high-pressure cylinder, the steam will become wet and the average cylinder wall temperature will not be excessive, even if steam jacketed. Hence, 5 per cent of tallow oil will usually be found permissible and advantageous.

High Superheat and Its Effect on Lubrication

The real problem begins when there is more than 100° F of superheat in the steam. For example, with a boiler pressure of 250 pounds, the steam temperature will be 405° F; if the superheater adds 200° F, total steam temperature is 605° F. At temperatures above 600° F it should now be obvious that an oil film of microscopic thickness must tend to roll up into little spheres, distill, oxidize rapidly, and produce carbon deposits.

Contrary to general belief, there appears to be no particular advantage in using the heaviest oils obtainable. Such oils contain a high percentage of carbon-forming material and tend to defeat their purpose for this reason.

The authors are of the definite opinion that high-temperature steam is not practical for reciprocating engines. With steam temperatures much above 550° F the oil film is far too thin and weak to prevent excessive wear. Furthermore, carbon accumulations necessitate frequent shut-downs for cleaning, and any theoretical advantage that may be gained in fuel economy is more than offset by expensive maintenance costs.

For single-cylinder engines, the added temperature should not be more than 50° F at the throttle valve if the total steam temperature approaches 500° F. For multicylinder or compounded engines, the added temperature should not be more than 100° F at the throttle valve if the total steam temperature approaches 500° F. This amount of superheat assures the engine of dry steam at the high-pressure valves and at least reduces a lubrication problem which cannot be solved with any degree of satisfaction. In fact, 100° of superheat may be considered high if the total steam temperature is above 550° F.

In this connection the authors have surveyed single-cylinder engines operating with superheated steam in the exhaust pipe. Engines of this type are nothing more than academic freaks. The only way to solve the lubrication problem is to cut down the initial superheat.

Recommendations for High-Pressure and Superheated Steam

In the approximate guide shown herewith only steam temperatures are considered. When steam is superheated the temperature is all important, and, in comparison, the pressure is a negligible factor. Before using this guide the text should also be consulted.

RECOMMENDATION GUIDE FOR HIGH-PRESSURE AND SUPERHEATED STEAM *

Steam Temperature at Throttle Valve, °F	*Flash Minimum, °F*	*Saybolt Viscosity at 210° F*	*Compounding Tallow, Lard (Per Cent)*	*Carbon Residue (Per Cent by Weight)*
450 to 550	550	180 to 225	5	4 max.
550 to 600	580	225 to 300	5 max.	4 to 5 max.
Above 600	600	250 to 350	None	4 to 6 max.

* The tests in the outline are made under the rules of the American Society for Testing Materials, and steam temperature at the engine throttle valve is stipulated for the reason that long steam pipes and similar factors alter the original temperature and condition of the steam.

Auxiliary Steam Engines

Where steam is available one often finds small steam engines to drive such equipment as condensate return pumps, vacuum pumps, and hoists. These are often neglected because of their small power consumption and low cost and ease of maintenance. These engines are often the source of high oil consumption. The graph in Fig. 4 may be used as a guide. As an example of the use of this table, assume an 8″ × 10″ pump. Follow across from the 8″ stroke and up from the 10″ bore. The intersection is closest to 35 strokes per drop of oil. The lubricator should be set for this feed.

In addition to the waste of oil, these feeds may be the source of excessive oil in the condensate return to the boilers.

Oil in Boilers

There is no definite agreement among authorities on the safe limit of cylinder oil which may be continually present in a boiler, for the reason that such factors as design, steaming conditions, effect of boiler compounds, and similar variables enter into the question. However, the following approximate safe limits are based on a cross-section of conservative opinions by boiler manufacturers, oil extractor manufacturers, feed water treatment chemists, and independent investigators. The oil and water ratios are based on the measurement that 1 grain per U. S. gallon equals 17.1 parts per million.

In water-tube boilers equipped with superheaters the oil content should be maintained at less than 5 parts of oil per million parts of water.

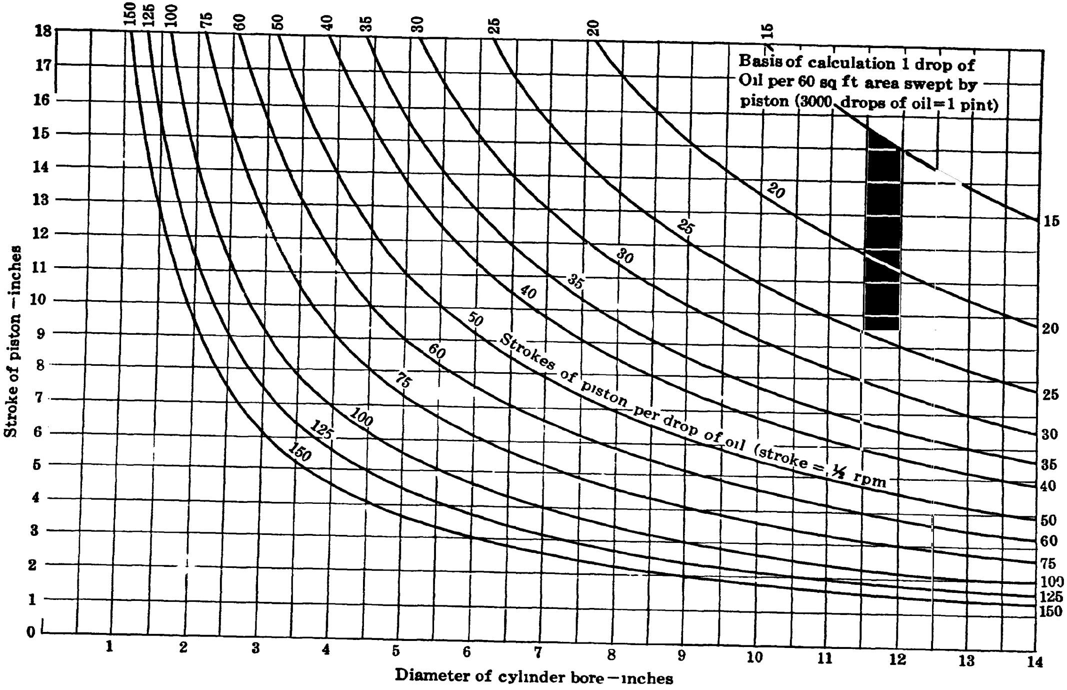


Fig. 4. Oil-application guide.

In water-tube boilers not equipped with superheaters the oil content should be maintained at less than 10 parts of oil per million parts of water.

In miscellaneous boilers generating at 200 pounds psi or above, the oil content should be not more than 10 parts of oil per million parts of water; below a pressure of 200 pounds per square inch not more than 20 parts of oil per million parts of water.

Examples are common in low-pressure boiler operations where no trouble has been experienced over a period of years with a constant ratio of 40 to 60 parts of oil per million parts of water; and some tests involving excessive oil-feed rates and inadequate extracting equipment have shown as much as 200 parts of oil per million parts of water. However, this practice is due to negligence and is unsafe and unnecessary, particularly when means and equipment are available to correct the possible danger.

Oil deposits are liable to lodge anywhere in a boiler, and, by acting as a binder for sludge, a tenacious accumulation may form to insulate the metal. On a tube or crown sheet, for example, a deposit of this type will prevent heat transfer and will thus cause the metal to burn, with resulting danger. However, the burning of the metal is due to inadequate filtering equipment, ignorance, or neglect, and generally the ratio of oil to water has to be maintained at a high figure to produce this effect.

Oil Extractors

To extract oil from condensate many types of equipment are employed, such as toweling, sponge materials, steam traps, weirs, baffles, and centrifugal vanes. The selection of equipment depends to a large extent upon the available space.

Where space is limited, toweling and sponge materials are commonly placed in weir tanks to extract oil from boiler-feed water, as, for example, in marine engine rooms. Where space is not limited, the most effective separator is the centrifugal vane, wherein the exhaust steam is forced into a whirling motion by stationary vanes built into a circular receiving vessel. The whirling motion imparted to the exhaust steam results in centrifugal action, which causes the heavier oil and water to travel outward and to run down the sides of the vessel and thence to the bottom, where it is drained off. Figure 5 is a diagrammatic example of a simple reverse-flow and baffle extractor located in the exhaust steam line.

To obtain very low concentrations of oil in the boiler-feed water, it is often treated with alum, which coagulates the oil and precipitates it.

With adequate equipment for extracting oil from boiler-feed water, the ratio of oil to water may be maintained at less than 20 parts of oil to a million parts of water. Many installations are in use which give results of less than 5 parts of oil to a million parts of water when using cylinder oils that contain 10 per cent of compounding. In these the oil is dispersed in the form of an emulsion.

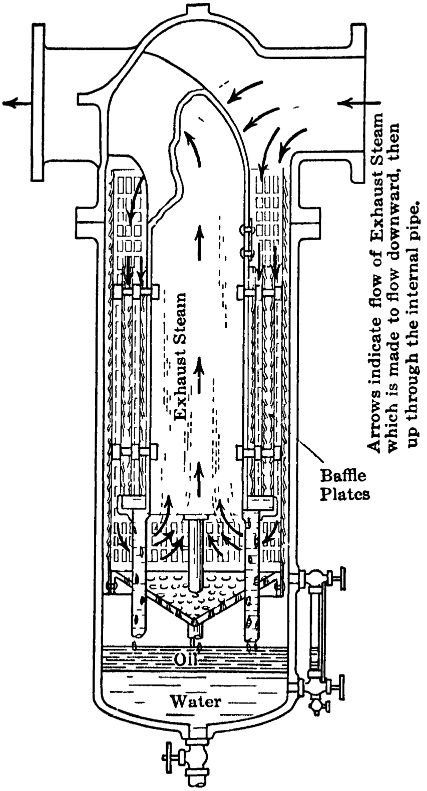

Arrows indicate flow of Exhaust Steam which is made to flow downward, then up through the internal pipe.
Exhaust Steam
Baffle Plates
Oil
Water

FIG. 5. Exhaust steam oil separator. In this type of oil separator the flow of exhaust steam is reversed. Oil tends to strike the internal pipe and run down the side into the reservoir, where oil and water may be drawn off at intervals. The separator is also equipped with metal projections, or baffles, which aid in trapping the tacky oil, allowing it to drip into the reservoir.

On the other hand, there are many power plants which are poorly equipped to extract cylinder oil from condensate. Straight mineral oils are therefore employed to secure flotation on top of the water and thereby simplify extraction. However, in wet-steam operations straight mineral oils are not capable of providing satisfactory lubrication. The compounded oils for wet steam form good emulsions and therefore create the problem of removing the emulsion from the boiler-feed water. This cannot be done without suitable equipment, as there is no mysterious property which will permit emulsion in the cylinder and rapid separation after leaving the cylinder.

For superheated steam operations the use of a straight mineral oil may be in order, but inadequate extraction effects a hazard in the boilers. Hence the problem of oil extraction should be carefully considered and not circumvented by inadequate makeshift methods.

Stand-by engines should be run at frequent intervals to prevent rusting of cylinder walls.

Engine Bearing Lubrication

Engines equipped with circulating oiling systems require an oil that will separate readily from water. This method of application is highly advantageous, for the reason that all bearings receive a continuous supply of cool oil; hence they operate under ideal conditions.

Most steam engines are large, have poor dimensional stability, and for this reason the alignment is rather poor and bearing clearances are about twice normal. Because of these clearances and relatively low rubbing speeds, oils of 300 S.S.U. and higher are recommended. The oil is usually contaminated with moisture coming from leakage by the packing gland and from normal condensation within the system. For this reason a turbine-grade oil should be used. Dirty locations and open crankcases indicate that an oil purification system be installed to maintain the oil in a usable condition. Otherwise a less expensive oil should be used and changed at frequent intervals. A good quality of oil, well maintained, should last for years.

In marine practice the engines are of vertical design, and condensed steam trickles down the piston rods into the bearings below; hence the general practice is to use an oil that will emulsify with water and thereby impart resistance against the washing-out effect that takes place. This result is accomplished by blending the mineral oil with 10 to 20 per cent of rapeseed oil. Other emulsifying agents are also used, but rapeseed oil is considered to be the most satisfactory.

Slow-speed running and idling should be avoided, as at low rubbing speed thin film lubrication of bearings occurs.

ENGINE BEARING RECOMMENDATIONS

Engine Size	*Method of Application*	*Saybolt Viscosity at 100° F*	*S.A.E. No.*	*Grade*
Small	Wicks, cups	300 to 400	20 to 30	Engine oil
Small	Splash	300	20	Turbine oil
Medium	Wicks, cups	400 to 600	30 to 40	Engine oil
Medium	Circulation, splash	300 to 600	20 to 40	Turbine oil
Large (vert.)	Wicks, cups, hand	700 to 1000	40 to 50	10 to 20% rapeseed oil
Large (vert.)	Circulation, splash	300 to 600	20 to 40	Turbine oil
Large (horiz.)	Circulation, splash	300 to 600	20 to 40	Turbine oil
Large (horiz.)	Wicks, cups, hand	500 to 800	30 to 40	Engine oil

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Steam Turbines

Steam turbines supply most of the vast electrical energy generated. In addition, many units are used as the power source to operate fans, pumps, ships, etc. Because of its simplicity a turbine is able to operate almost continuously at speeds and temperatures which would cause failures in other types of equipment.

The turbine itself consists of a shaft to which are attached rows of blading surrounded by a casing. The shaft is supported by two bearings, and a thrust bearing is provided.

Turbines may operate at temperatures from 240° F for low-pressure turbines to 1000° F for high-pressure units.

The turbine lubricant has three functions to perform: to provide lubrication for bearings and reduction gears; to act as a hydraulic fluid for the governor mechanism; and to act as a heat transfer agent in cooling the shaft.

Turbine Bearing

Most small auxiliary turbines have ring-oiled bearings which may or may not be water cooled. The bearings operate hot owing to the heat induced from the shaft and the casing. Water-cooled bearings seldom run over 150° F, whereas without water they may operate as high as 240° F. The oil is therefore subject to severe oxidation. The speed is usually above 3500 rpm. Bearing loads are light, normally not over 180 psi of projected area.

Large turbines and smaller units where continuity of service is paramount have pressure circulation of the oil to the bearings. An auxiliary oil pump is supplied so that the bearing may be flooded before starting and oil circulation maintained to cool uniformly when the turbine is stopped. A main oil pump maintains the pressure while the turbine is operating. This type of oiling system makes the use of an oil cooler to maintain oil temperatures below 175° F.

Most turbines have thrust bearings of either the fixed or tilting-pad type. All radial bearings are babbitted and fitted to an initial clearance of 0.001 inch per inch of shaft diameter, and rebabbitted when the clearance increases to 0.002 inch per inch of shaft diameter.

Turbines operate on thick film lubrication, and wear occurs only on starting and stopping. In larger turbines the "start and stop" wear is eliminated, as the auxiliary oil pump supplies sufficient pressure in the load zone to float the shaft.

Much thought and development have gone into the design of a turbine bearing. The bearing should not be altered. This rule is an exception, as changing the design or material of many bearings in machinery will improve bearing performance considerably.

Turbine Gearing

Turbines depend upon high speed for their power; therefore it is necessary in many installations to reduce the speed through reduction gears. Where the gear reduction unit is an integral part of the turbine and tied into the turbine oiling system, the choice of the lubricant is a compromise between the gears and other parts of the turbine. Where the gear case has a separate oiling system, it is possible to use one oil for the turbine and another oil for the reduction gears. The gears are very accurate and highly finished, enabling them to carry high loads continuously with a light film of oil. Most gears are lubricated with fine oil spray, supplied from an oil line under pressure and directed at the point where the gears meet.

Turbine Governors

To control the speed and power of the turbine there is a governor system operated by oil pressure, actuating pistons which move linkages to control the admission of steam or water to the turbine. In addition, there is a mechanical governor which prevents excessive overspeeding in event of any failure of the main governor.

Deterioration of Turbine Circulating Oils

The principal factors which have a deteriorating effect on turbine circulating oils are:

Heat.

Oxygen in the air.

Catalytic effect of impurities and contact with metals.

Other influences are of a minor and varied nature, such as chemical effects in the presence of small metallic particles, entrance of water, and entrance of such foreign impurities as flange and pipe jointing materials. Turbine oil performance is influenced by contamination, and the oiling system must be protected, insofar as this is reasonably possible, against contact with any and all types of foreign impurities, particularly materials which may be soluble in oil, water, or both. When a turbine system is cleaned or repaired, careful supervision should be exercised to see that no contaminating agents, such as traces of soap compound and pipe jointing materials, are left in the system. A foreign substance of the soluble type is often capable of ruining the complete oil charge. However, the effect of heat is by far the most influential factor in shortening the life of turbine oils, and discharge oil temperatures from bearings and gears should be maintained below 180° F. At temperatures above 180° F, turbine oils which would otherwise maintain their stability over a period of years will have their life reduced in direct proportion to the increase in temperature. At temperatures above 220° F the condition of the oil should be watched closely.

The rate of oxidation of the oil is affected by the temperature of the steam used in the turbine. The oil in a turbine with steam temperature of 800° F will oxidize more rapidly than the oil in a turbine with steam at 600° F, even though both systems may have an oil temperature of 150° F. With the large volumes of oil being circulated for cooling there can be local "hot spots" far in excess of the average temperature.

A source of oil oxidation in some older turbines is the governor mechanism. The oil is held for long periods of time, at elevated temperatures, back of the pistons. When this oil finds its way back to the general supply it accelerates the rate of oxidation of the complete oil change. This difficulty is prevented in newer turbines by having some oil circulate through the governor mechanism at all times.

The products of oxidation may cause fouling of the governor mechanism, which interferes with the regulation of the turbine. These same products interfere with heat transfer and may be suspected when additional cooling water is required in order to maintain oil temperatures.

With a nonadditive-type oil it is not unusual to find deposits in a turbine system. An oxidation-inhibited turbine oil should be used to minimize the chance of the formation of oxidation products.

Composition of Turbine Oil Sludges and Emulsions

Turbine oils are refined to impart maximum stability by extracting the unsaturated hydrocarbons from the original crude. These unsaturated hydrocarbons may be likened to starving molecules which were created without their full share of hydrogen, and as a result they are ready to satisfy their appetite on other digestible atoms of which oxygen from the air forms a convenient source of supply. When this chemical reaction is accomplished, the unsaturated hydrocarbons stabilize themselves and form a new compound known as sludge. The laboratory analysis given here shows the composition of a typical sludge formation taken from the oil tank of a turbine oiling system.

Material	*Percentage*
Oxidized oil	8.0
Water	22.0
Oil (in good condition)	69.5
Ash [1]	0.5
	100.0

[1] Analysis of the ash showed 0.2% iron oxide, 0.12% copper, and 0.18% of unidentified inorganic material. Most of the materials in the ash were in the form of metallic soaps before reduction by heat in a crucible.

The composition of sludge is often very complex, particularly when the sample contains metallic soaps and similar compounds as a result of the combination of the unsaturated hydrocarbons with elements other than oxygen.

The effect of heat is that of an accelerator in producing oxidation. The higher the temperature of the oil, the more rapid the oxidation process.

Sludge or oxidized oil is also an active emulsifying agent. The great majority of emulsions are a combination of sludge, water, and oil. In similar manner the majority of emulsification troubles which occasionally take place in turbine oiling systems are brought about by oil breakdown and the entrance of water. In isolated cases the cause is sometimes traceable to the entrance of a foreign substance, as, for example, cleaning compounds, or linseed oil, which is sometimes used to paint tanks for rust prevention. However, most emulsions are a simple combination of sludge, oil, and water.

There are three main sources of water in a turbine oiling system: (1) condensation from warm humid air within the oil system being cooled and condensing; (2) a leaking tube in the oil cooler; and (3) steam gland leakage.

Breaking an Emulsion

Heat is required to break an emulsion, and although not common in land installations, many marine turbines are equipped with a reserve oil tank containing heating oils. In the event of serious emulsification trouble, the oil may be bypassed into this tank and the emulsion broken to a large extent by separating the sludge and water at temperatures of 170° to 212° F and then allowing the charge to cool and settle. Continuous operation of the centrifuge, with the oil as warm as possible, will materially assist in eliminating the sludge and water from the oil. In the event of a persistent emulsion, the oil must be considered unsuitable for continued service and changed at the first opportunity.

Rusting in Turbine Oiling Systems

A turbine oil is made to separate from water readily to prevent the formation of emulsions, but this leaves the water free to promote the rusting of metal surfaces.

To overcome this difficulty the addition of antirust inhibitor is the proper procedure in turbine oils. In this application, the fact has been established that, when solvent refined turbine oils are new, they do not readily spread over metal surfaces. They have a high surface tension and lack wetting ability. When steel and iron surfaces are new, they appear to be very active and susceptible to chemical reactions, and the first reaction is quick rusting, particularly if moisture is present. To meet this possibility, refiners incorporate a small amount of antirust compound in the turbine oil, just sufficient to increase oil wetting properties over the metal surfaces and thereby prevent rusting.

Almost any mild acidic material will produce a protective plating action on new iron and steel surfaces, but the compounds actually employed in turbine and gear oils are selected materials which have the least possible effect on the physical characteristics of the oil. Such products as linseed oil will accomplish the desired result, but they will cause the oil to emulsify in the presence of water.

Once the metal surfaces have been exposed to a suitable antirust compound they apparently lose their chemical activity by immediately absorbing a protective coating. From this point on they remain dormant to any further violent or sudden inclination to rust easily in the presence of oil and water.

Turbine Oil Foaming

The reasons that oil starts foaming are not too well understood. Some of the more common causes of foaming are listed below.

1. Foaming can be brought about by the sudden addition of too much new oil in the system. Fresh oil should be added gradually to

a circulating oiling system to give the combining molecules a chance to stabilize themselves quietly.

2. When oil return lines are placed too high above the receiving tanks the waterfall effect will sometimes aerate the oil and cause foaming. This operating difficulty is generally a minor mechanical problem which can be remedied without much trouble.

3. Excessive bearing clearances pull more air into the oil than can be released within the system.

Most turbine oiling systems have some foam on top of the oil level in the tanks. Foaming becomes a problem only where the foam overflows through vents, etc. This causes loss of oil but may also be a distinct fire hazard.

Excessive foaming may be stopped by use of an antifoam agent. However, the cause of foaming should be determined and corrected at the earliest opportunity.

Turbine Oil Purification

Turbine oil purification is practiced for the removal of extraneous material, such as water and dirt, and the removal of the oil components which promote oxidation, such as acidic compounds.

Sludge is eliminated from a turbine oiling system in several ways. Each designer has individual ideas on the subject, and one method uses a large settling tank with a steep cone-shaped bottom. Sludge or oxidized oil is for the most part heavier than oil and as a result drops to the lowest part of a system, or gathers where there is least agitation. Not all broken-down oil molecules drop out easily; some remain in solution while the oil is warm but drop out as the oil cools and becomes motionless.

The use of a centrifuge is another highly effective method which quickly removes both sludge and water from a turbine oiling system. These machines should be operated at approximately half their rated volumetric capacity to secure best results. If run with a full flow that equals the rated capacity, they are not capable of removing the maximum amount of sludge from the oil that passes between the centrifuging vanes. The larger the centrifuge the better. For turbine oiling systems they are very effective in prolonging the useful life of the oil charge, and they require very little space. One should never skimp on the size of a centrifuge, and should maintain the oil above 120° F.

Cloth filter bags and settling tanks are also used for land installations, but they are too cumbersome for marine service. Clay type of filters are very effective in removing the acidic components of nonadditive oil. The additive types of oils do not normally oxidize, and therefore there is little need for clay filtration.

The intermittent or continuous filtration of a turbine oil is in itself a refining process and materially prolongs the life of the charge by removing the small amount of sludge which forms from day to day. Hence, any method of purification, or combination of methods that will remove this material, is advantageous.

Large turbine oil charges are sometimes water washed in a separate tank on the theory that mixing the oil with water lowers the acidity by washing out the acidic compounds which increase as the oil oxidizes with age. While such installations accomplish this result to a certain degree, there does not appear to be any conclusive evidence that longer life of the charge is secured. Water is the most powerful solvent found in nature, and, since a little water seeps into turbine oiling systems from time to time, this amount may also account for a lowering of acidity. However, in contact with metals, water is a detrimental factor, and every effort should be made to eliminate it from the oil charge to avoid unnecessary complications.

Cleaning Turbine Oiling Systems

When a turbine is new, the oiling system should be cleaned out with a charge of inexpensive spindle oil containing an antirust compound. Circulating this type of oil through the pipes and passages for 3 or 4 hours removes any objectionable impurities which may be present. After the spindle oil is drained from the system, the oil tanks and all parts which are reasonably accessible should be cleaned with dry rags before the charge of new turbine oil is installed.

This procedure may seem rather laborious, but protective compounds are sometimes used for the prevention of rust on turbine parts during shipment. Furthermore, metallic particles, sand from casting pores, and other materials may be present. Hence the precaution of washing out the entire system with spindle oil is a worthwhile practice.

For the annual cleaning of tanks, pipes, passages, and mechanical parts, the use of dry rags is recommended. Naphthas, kerosene, or similar cleaning fluids may be used on parts which are accessible on the floor or are located in the open air. Under no circumstances should cleaning compounds be used which might contaminate the oil charge, and every section must be left dry.

There are several compounds on the market for removing oil sludge deposits which form on oil cooler tubes, and manufacturers of these specialties issue instructions for their use. The usual formula for such compounds is 50 per cent trisodium phosphate and 50 per cent soda ash mixed with hot water in the proportion of 1 part of compound to 5 parts of water. The strength of the mixture and the amount of boiling required with the aid of a steam coil depend upon the persistence of the deposits. The best practice is to remove the tube bundle and do the cleaning work in a suitable bath. After tube bundles have been cleaned, the cooler and tubes must be washed out very thoroughly with fresh water for the reason that any soap materials left in the system are capable of producing an emulsion in the presence of moisture and, in fact, of ruining the entire oil charge.

Unusual care should be taken in cleaning a turbine. Procedures will vary, depending upon the type of cleaning required and the equipment available.

Under no condition should the cleaning be left to inexperienced personnel or to unsound methods.

Steam Turbine Oil Recommendations

Steam turbine oil recommendations are rather simple for the reason that modern oiling installations have reached a high degree of mechanical perfection. Bearing clearances are comparatively liberal to allow rapid heat removal by the oil; coolers are installed to maintain low operating temperatures for the oil; filters are installed to purify the oil; and large tanks are installed to store the oil. Much of the success of steam turbine lubrication is due to these features, and, of course, to the fact that speeds are high and maintain a powerful pumping action on the oil films around the journals.

In geared turbines the cool oil cascades into the meshing gear teeth by means of jets, and only in exceptional cases is it necessary to use an oil heavier than 500 S.S.U.

Turbine oiling systems contain from 50 gallons to more than 2000 gallons of oil, and the great majority run for years with little more than routine attention to cleaning the system, governor parts, and coolers about once a year.

The recommendations in the accompanying table are standard for turbine-grade oils, depending upon the more exact instructions issued by the particular designers of the turbine.

RING-OILED BEARINGS

Temperature	*Saybolt Viscosity at 100° F*	*S.A.E. No.**
Normal	150 to 300	Below 10 to 20
Above 180° F	500 to 1000	30 to 50

CIRCULATING SYSTEMS

Type of Turbine	*Saybolt Viscosity at 100° F*	*S.A.E. No.**
Direct-connected	150 to 200	Below 10 to 10
Geared (single-reduction)	300 to 400	20 to 30
Geared (double-reduction)	400 to 550	30 to 40

* S.A.E. oils should not be put into turbine systems.

Turbine Oil Specifications

The physical tests listed in the table are discussed and their purpose explained in detail in Chapter 10. In the present chapter they are applied to three grades of new turbine oil. However, these tests are only a guide to anticipated performance. There is no test or combination of tests which will guarantee definite results in actual service. Most turbine manufacturers recommend that additive types of oils be used.

ANALYSES FOR THREE GRADES OF STRAIGHT MINERAL TURBINE OILS

Test	*Light*	*Medium*	*Heavy*
Saybolt viscosity at 100° F	150	300	400
Saybolt viscosity at 210° F	43	51	58
Flash	350° F	420° F	430° F
Fire	455° F	495° F	500° F
Pour point (max.)	30° F	30° F	30° F
Neutralization number	0.05	0.05	0.05
Rusting	Passes	Passes	Passes
Oxidation	1000 hrs.	1000 hrs.	1000 hrs.

Analysis of Used Turbine Oil

The most popular and widely used method of judging the rate of deterioration in a turbine oil is the "acid number." When oil breaks down as a result of slow oxidation it develops organic petroleum acids which are complex in structure and are generally distinguishable by a slightly pungent odor. An excessive amount of this acidity is almost invariably the forerunner of sludge. For example, a sudden rise in acidity and viscosity generally indicates that sludging may be anticipated, and the charge will require careful watching for further signs of actual breakdown, which, incidentally, may take place without further warning.

Figure 1 shows a typical service record of a heavy turbine oil. It should be noted that there is a steady increase in viscosity and acid number in the nonadditive oil, which will continue, sludging, at some rate, depending upon the type of oil. In the additive oil, no significant changes occur in seven years. A small change in the acid number or viscosity would be cause for investigation of the oil.

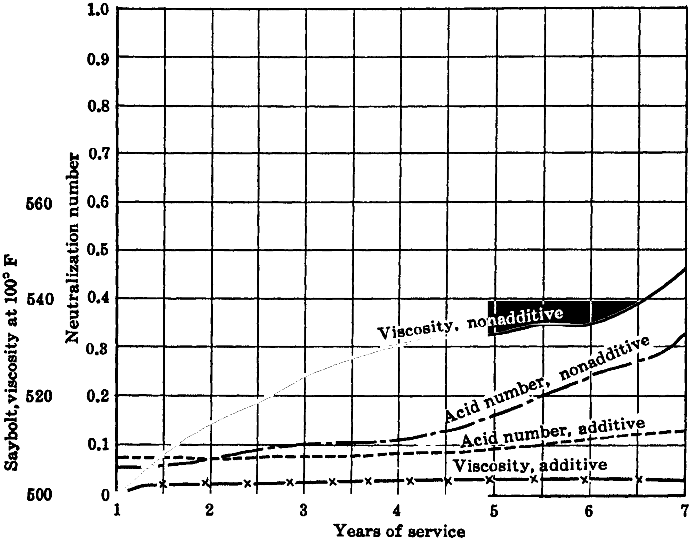

FIG. 1. Service records of nonadditive and additive types of heavy turbine oils.

Interfacial Tension

The interfacial tension test is the most valuable single test that can be used to evaluate a turbine oil. It is generally agreed that, when the interfacial tension is between 15 and 20, deposits may or may not be forming in the system. Safe practice would call for an oil change in this range. Below 15, deposits are forming in the system and trouble can be expected.

In the nonadditive oil darkening in color can be expected. If an additive-type oil darkens it is an indication that a drastic change is taking place within the oil, or that the system has been badly contaminated.

1. Duplex magnetic strainer
2. Relief valve
3. Service pump—motor operated 60 gpm
4. Stand-by pump—motor operated, 60 gpm
5. Duplex strainer
6. Orifice, diam. 15/32″
7. Oil coolers
8. Oil @ 70 lbs. to governor and trips
9. To low oil-pressure control value
10. Continuous overflow
11. Oil to bearings
12. To hp turbine bearing
13. To hp turbine bearing
14. To generator bearing
15. Drains
16. Centrifuge

A. Thermometer in bearing drains ▯
B. Sight flow indicator in bearing drains ф
Lubrication System

Lubricating System
8000 h.p. turbine electric ship

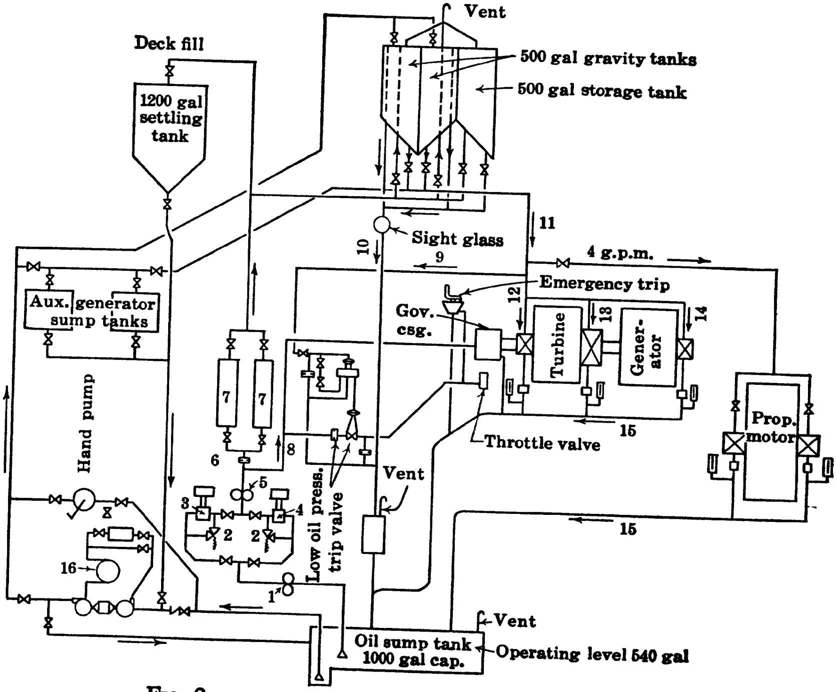

Fig. 2.

Water and sediment tests are many times run on used turbine oils. The presence of water indicates a steam or water leak. An analysis of any sediment found will often indicate the source of the contamination within the system.

Special conditions may arise which call for extensive tests not routinely run on turbine oils.

Once a turbine oil has deteriorated, it is uneconomical to add large quantities of new oil in order to improve the oil. The oxidation products in the used oil serve as a catalyst to break down the new oil. As little as 7% of a used oil may shorten the life of a new oil as much as 20%.

Figure 2 is one of many types of oiling systems employed on a turbine electric drive for a ship.

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Hydraulic Turbines

Hydraulic turbines may be divided into two main classes, namely, the impulse and the reaction types. The impulse turbine, which is generally known as the "Pelton wheel," is used only for very high heads of water and is always mounted in a horizontal position. The wheel itself is equipped with buckets against which water at high velocity is directed by a nozzle, thereby imparting rotation to the wheel. Ring-oiled bearings are generally used for small wheels, and circulating systems for very large installations. Because the flow of water is at right angles to the axis of the turbine shaft, there is very little end thrust, and lubrication of the radial and thrust bearings is not difficult. A medium-viscosity oil of 150 to 300 seconds at 100° F is satisfactory, and the general practice is to use the same oil as a fluid medium in the governor system.

The reaction type of hydraulic turbine, which is used for low and medium heads of water, is the most common type of water wheel. The runner, which holds the blades through which the water flows to impart motion, may be either of the Frances or propeller type, the latter being similar in construction to the propellers used for driving ships. The flow of water is controlled by guide vanes or gates which may be opened or closed, depending upon the load on the turbine.

When analyzing hydraulic turbines from the lubrication standpoint there are four factors to be considered: (1) the thrust bearing, (2) the radial guide bearings, (3) the submerged bearings, and (4) the governor system.

For vertical turbines, which are in the great majority, the thrust bearing supports the entire weight of the generator, turbine, and shaft. If lubrication fails, not only must the turbine be shut down, but considerable damage may result. The trust bearings, of which the Kingsbury and the Gibbs are examples, operate on the fluid film principle, and the entire load is carried on a thin film of oil. Such bearings are always submerged in a bath of oil, and the oil is cooled either by means of water coils in the housing or by circulation of the oil through a cooler located at some convenient point.

The guide bearings maintain the vertical shaft in its correct position and are not subjected to any great unit load. In many small turbines the guide bearings are made of a rubber compound or lignum vitae and are lubricated entirely by water or by a combination of lubricant and water. Where babbitted guide bearings are used, they are lubricated either by means of an independent system or by oil from one common oiling system. Guide bearings generally use the same oil that is employed on the thrust bearings, and a medium-bodied oil having a Saybolt viscosity between 150 and 300 seconds at 100° F is usually satisfactory.

Guide vanes are submerged in water and are lubricated by means of grease forced through the necessary lengths of piping. Since the temperature of water is low in winter, the grease should be fluid at low temperatures to permit application through the long lengths of piping. Also, because the grease in these bearings is subjected to the washing action of water it should be insoluble in water. Calcium or lithium soap greases should be used, as they resist displacement by the water.

The governor controls the speed of the turbine by controlling the amount of water flowing through. The mechanism is of the hydraulic relay type similar to that used on steam turbines. Oil is used as a fluid medium, and as the governor flyballs change their position in response to any speed variation in the turbine, a relay valve opens or closes, regulating the flow of oil to a secondary valve. This valve controls the flow of oil under pressure to the pistons regulating the guide vanes, which in turn permit a greater or lesser quantity of water to pass through the turbine runner.

Wherever possible, one oil is used both for lubricating the guide and thrust bearings and as a fluid medium in the hydraulic governor system. However, for units operating in cold climates where the turbine room may not be heated, a light oil with a low pour point is a necessity for governor mechanisms.

In contrast with steam turbine oil, the oil used for hydraulic turbines is not subjected to heat from an outside source, and little or no moisture gets into the oil. Therefore, insofar as lubrication requirements are concerned, hydraulic turbines are not nearly as exacting on the oil as are steam turbines. In fact, they may be satisfactorily lubricated with oils of less refinement, although the best quality is to be preferred.

RECOMMENDED OILS FOR HYDRAULIC TURBINES

Part	*Method of Application*	*Oil*
Thrust bearings, Kingsbury, Michell, Gibbs, General Electric, ball and roller types, guides, and journal bearings	Circulation Bath Oil cups	150 to 300 S.U.S. turbine oil
Plain collar-thrust bearings	Circulation Bath	500 to 800 S.U.S. turbine oil
Hydraulic governors	Fluid medium	150 to 300 S.U.S. turbine oil [1]
Hydraulic controls	Fluid medium	300 S.U.S. turbine oil [2]
Open gears, racks	Brush	Residual oil, approximate Saybolt viscosity 1000 sec at 210° F
Enclosed spur gears	Splash	500 S.U.S. turbine oil
Worm gears	Splash	150 S.U.S. at 210° F cylinder oil
Adjustable blade hubs	Bath	150 S.U.S. at 210° F [3]
Lignum vitae bearings	Oil	300 to 500 S.U.S. marine engine, containing 10 to 20% rapeseed
Lignum vitae bearings	Grease	Calcium soap base containing not less than 4% graphite

[1] Manufacturers of hydraulic turbines sometimes specify heavier or lighter oils for hydraulic governors. Such specifications should be followed. For low-temperature operations, particularly in thrust and shaft bearings, a 150 S.U.S. oil having a pour point of −20° F is sometimes necessary. In extremely low-temperature operation even lighter oils may have to be used.

[2] For low-climatic-temperature conditions the hydraulic system which operates distant gate valves, etc., should be filled with a light ice machine oil having a Saybolt viscosity of not more than 100 seconds at 100° F and a pour point below −25° F. For extremely low climatic temperatures the hydraulic system which operates distant gate valves, etc., may require transformer oil having a Saybolt viscosity of approximately 50 to 60 sec at 100° F and a pour point below −40° F.

[3] One or two builders specify grease for hub lubrication. For these applications a soft calcium or lithium soap grease containing an S.A.E. 20 oil with a low pour point is suggested. Similar greases manufactured with a mixed base of calcium and sodium soaps are also worthy of consideration. Owing to the controversial nature of hub recommendations, the builder's advice should be carefully studied.

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Hydraulic Systems and Fluid Couplings

Hydraulics is the science which deals with fluids in motion. Equipment utilizes hydraulics for transmitting force and motion. A knowledge of the fluids used as the power-transmitting medium is of importance because of the increasing applications of hydraulics to machinery.

The basic parts of a hydraulic system are relatively few. These parts may be combined to form a rather complex system. A simple hydraulic system would consist of a storage tank for the fluid, a pump to build up pressure, a piston and cylinder or a hydraulic motor, plus necessary valves and piping to connect the parts.

There are two types of hydraulic systems. One is the hydrostatic, where the pressure is used to transmit force. An example is the hydraulic automobile jack. The force applied to the small piston is multiplied when applied to the greater area of the larger piston. The second hydraulic system is the hydrodynamic type, in which considerable velocity is imparted to the fluid. This energy is utilized when the rapidly moving fluid strikes against some part of the system. Hydraulic couplings and torque convertors are examples of this type.

The fluid used in a hydraulic system must perform three functions:

1. Transmit power.
2. Lubricate the moving parts.
3. Protect the metal surfaces from corrosion.

Water, as the fluid, may be used in simple, low-pressure, low-speed systems, such as a hydraulic elevator. As pressures and speeds increase, the unit loading on the moving parts increases. Closer clearances and finer finishes are required. It is most necessary to use a good lubricant, as any wear rapidly decreases the efficiency of a hydraulic system.

Consideration must be given to the following properties in selecting a hydraulic fluid:

Viscosity
Viscosity index
Oxidation stability
Lubricating value
Rust- and corrosion-preventative properties
Foaming
Ready separation from water

Viscosity

Viscosity is the friction of a fluid, as discussed in Chapter 10. High-viscosity fluids will cause excessive power losses and temperatures. Too low a viscosity under high pressures will permit wear. All the fluid frictional losses must be dissipated as heat. This causes the viscosity to decrease until a heat balance is reached. As an example, a system operating on a 150 S.S.U. at 100° F oil with a running temperature of 160° F could be expected to operate at 200° F when a 300 S.S.U. at 100° F oil is used. This does not hold true where heat is induced, as in die-casting machines, or where oil coolers are employed.

Viscosity Index

A high-viscosity-index oil is indicated where wide variations in air temperatures are encountered. Examples of such equipment are trucks, aircraft, and construction machinery. Most industrial equipment operates in ambient temperatures of 60° to 100° F, where viscosity index is of minor importance.

Oxidation Stability

Temperature, high rates of circulation, and the continuous reuse of the fluid, together with the exposed metal surfaces, which may act as a catalyst, cause rapid deterioration of oils unless an oxidation inhibitor is employed. Systems which leak require high volumes of make-up oil. This automatically provides for oil changes, so that inhibited oils are not required. The oil used in tight systems should pass the "turbine oil stability test."

Oxidation products must be kept out of hydraulic systems. They prevent heat transfer, plug orifices, and cause gumming and sticking of valves.

In many hydraulic systems an oil cooler and filter are used to help maintain the fluid in a usable condition.

Lubricating Value

The lubricating value of an oil is a primary function of viscosity. In a hydraulic system the pumps determine the lubricant. Because of the many types, pressures, clearances, and finishes, no one lubricant can be used for all conditions.

Type Pump	*Normal Viscosity Used*	*Viscosity Range*
1. Vane[1]	150 S.S.U.	100 to 225 S.S.U.
2. Axial piston (Fig. 1)	300 S.S.U.	200 to 500 S.S.U.
3. Radial piston (Fig. 2)	550 to 800 S.S.U.	150 to 1250 S.S.U.
4. Gear (Fig. 3)	300 S.S.U.	150 to 900 S.S.U.

[1] See Fig. 1, Chapter 24.

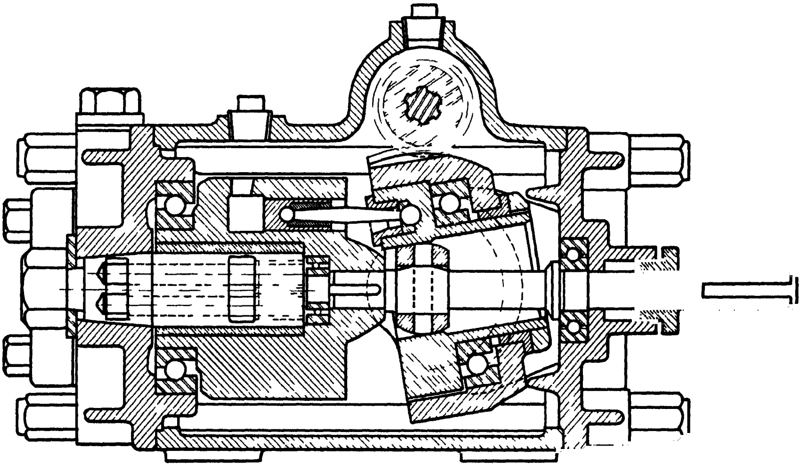

FIG. 1. Axial piston pump.

Rust- and Corrosion-Preventive Properties

Water may be present in a hydraulic oil system, either from condensation or from leaky oil coolers. Any rusting will destroy the finished surfaces, and rust particles will plug valves. The oil should pass the rusting test as developed in Chapter 11.

Foaming

Any air which is entrained in the oil and not released in the tank is pumped into the system. This causes compression of the fluid with resultant erratic movements. Uniform movement is required in machine tools and time cycles on production machines. Loss of oil

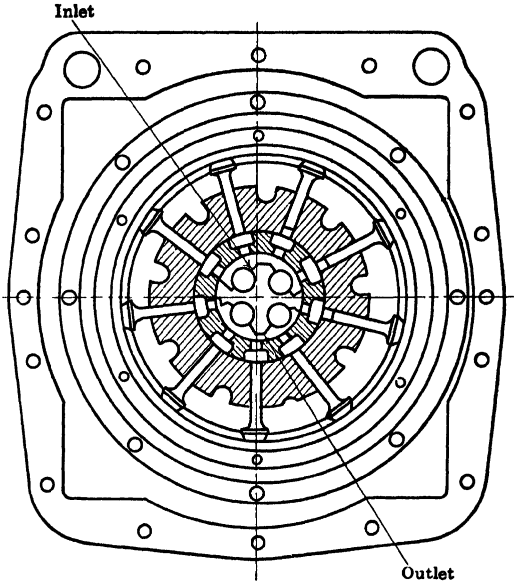

FIG 2 Radial piston pump.

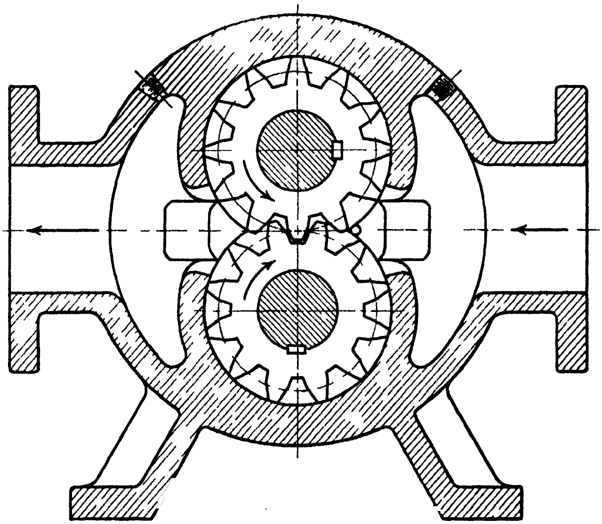

FIG. 3. Gear-head pump.

due to foaming may create a fire hazard in die casting machines and an accident hazard in any machine.

Water Separation

Water is frequently found in the oil system. This can come from two sources: (1) a leaky oil cooler or (2) condensation. The oil should separate from the water readily, so that the water can be drawn off. Water should not be permitted to accumulate, since stable emulsions are formed as the oil and water pass through the pumps. Oil temperatures of 130 to 140° F are optimum for the separation of the water from the oil.

Oil Maintenance

The oil must be kept free from dirt, so that closely fitted and highly finished surfaces will not be damaged. The system should be kept free of water to prevent rusting and the formation of emulsions. Depending upon the size of the system, filters, settling tanks, and centrifuges should be considered in helping to maintain the oil in a usable condition.

Fluid Couplings

Fluid couplings permit a high starting torque, a shock load, and a speed differential between the driving and the driven member. The lubricant requirements for these mechanisms are the same as those for a hydraulic system, except for the viscosity, which should be between 100 and 150 S.S.U. at 100° F.

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Air Compressors and Vacuum Pumps

There are two main types of air compressors, reciprocating and centrifugal. These may be water or air cooled. In small reciprocating units the cylinder and crankcase are lubricated by either a common splash or a pressure system. In the larger units separate oil systems are provided to lubricate the cylinders.

Once oil is introduced into a compressed air system it is impractical to remove all traces of oil from the air. Where so-called oil-free air is desired, most of the oil can be removed by various types of oil separators.

Dirt is extremely destructive to all types of compressors. Efficient air filters should be installed on the air-intake side of the compressor.

Centrifugal Compressors

There are four main types of centrifugal compressors.

(1) The sliding-vane type (see Fig. 1) consists of a rotor mounted eccentrically in a housing. The rotor is slotted, and vanes are free to move in and out to conform to the housing. Because of the high sliding velocities a good oil film must be maintained. Oil may be metered to the pump by means of a sight-feed lubricator, metering pump, or air-line lubricator. A 300 to 500 S.U.S. at 100° F oil should be used. These compressors may run from a few hundred to 3600 rpm, and pressures up to 125 psi may be developed.

(2) Positive-displacement compressors (Fig. 2) have two rotors, with two or more lobes. The rotors are driven in opposite directions by two gear-connected shafts. The lobes do not touch each other or the housing. Close clearances are maintained between the lobes and the housing, and no internal lubrication is required. The speed ranges from 250 to 1200 rpm. The bearings and gears can be lubricated with the same oil, one of 300 to 500 S.U.S. at 100° F. These compressors are used where large volumes of gases are required at low pressures,

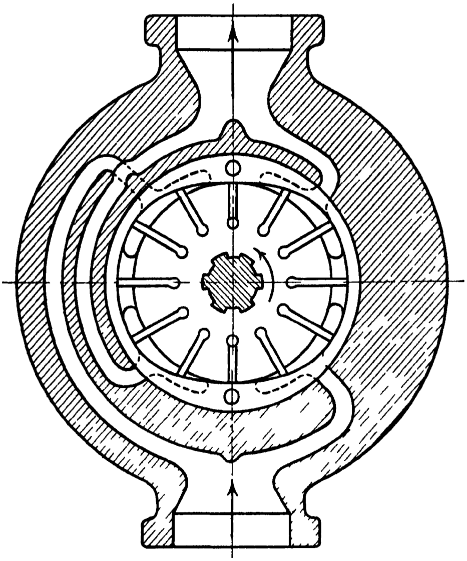

FIG. 1. Sliding-vane centrifugal compressor

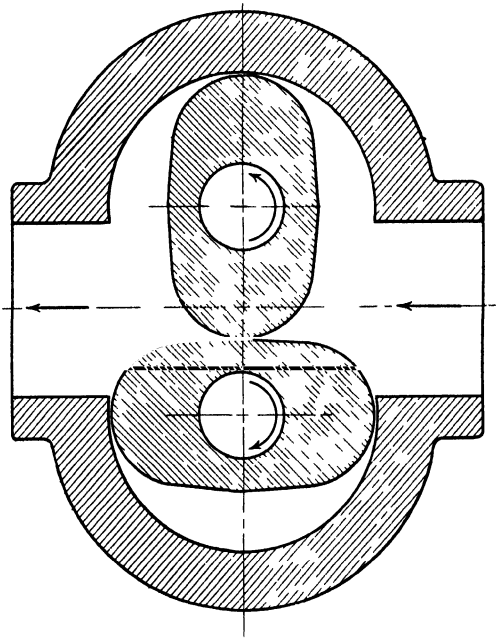

FIG. 2. Positive-displacement compressor.

5 to 10 psi. These compressors can handle relatively dirty gases with a modest rate of wear because of the built-in clearances.

(3) The centrifugal compressor consists of a rotor fitted with suitable blades turning in a housing. Air enters near the shaft and is thrown outward with considerable force. No internal lubrication is required. The bearings should be lubricated with 150 S.U.S. at 100° F additive-type oil. These are high-speed machines, and the intake air should be free from dirt in order to eliminate abrasive wear. Some of these units can deliver 125,000 cfm at 30 psi and may require 15,000 horsepower to drive them.

(4) The axial-flow type of compressor is similar to a reaction turbine. The air flows parallel to the shaft through a series of blades on the rotor. The lubrication requirements are the same as those for a centrifugal compressor.

Reciprocating Compressors

In reciprocating compressors it is necessary to pay special attention to the lubrication of the cylinder wall and piston rings. In the cylinder of an air compressor the oil is not washed out as rapidly as in a steam engine, nor is it burned as in the cylinders of an internal-combustion engine. Actually the oil film is maintained on a cool surface.

An excessive oil-feed rate is not only wasteful but is actually harmful. When more than that which is required to maintain a good oil film on the cylinder walls is supplied, the excess enters the coolers and receiver and also lodges in all clearance spaces and on the valves. In combination with fine particles of dust which may not be kept out of the air entirely, gummy deposits eventually collect. It is therefore very important to bear in mind that two or three drops of oil per minute will lubricate the largest compressor cylinder made. When the supply is excessive, the coating of dust and oil which collects on the cooling surfaces reduces heat transfer and consequently raises the air-discharge temperatures. This lowers the capacity of the machine and necessitates cleaning. Extreme cases of neglect and overlubrication have been known to cause fires and even explosions in compressor systems. A short description of how this can occur is given later in this chapter under the heading "Air Compressor Fires."

Discharge Temperatures

Every compressor system, large or small, should be equipped with a thermometer in each discharge line. This precaution serves the same purpose as a steam gage on a boiler. If the air temperature rises above normal it is an indication that recompression is taking place owing to the discharge valves not closing properly, or "wire drawing" may be taking place owing to deposits closing the discharge passages, or the cooler may be fouled. Most compressors are operated "blind." Thermometers not only provide a safety precaution against the possibility of a fire or explosion but they register mechanical faults which might otherwise pass unnoticed.

The table indicates the temperature range which can be expected at specified pressures. In practice there may be small deviation due to installation and operating procedures.

THEORETICAL AIR-CYLINDER TEMPERATURES AT END OF PISTON STROKES

Air Pressure	*Temperature, Single Stage, °F*	*Temperature, Two-Stage Inter-cooled to 60° F*
10	145	
30	255	
50	339	188
80	432	224
100	485	243
150	589	279

Types of Oil to Use in Air-Compressor Cylinders

There are two considerations in selecting an oil for cylinder lubrication: what the discharge temperature is and whether the air is wet or dry.

In high-compression stages the presence of free water is sometimes a factor to reckon with in the high-pressure cylinders. This water is liberated by the decrease in air volume, which causes the moisture in the original air to condense. By addition of a small percentage of fatty oil, such as 5 per cent of lard oil, an emulsion is formed with the water, and this oily emulsion sets up an appreciable resistance to being washed off the cylinder walls. As a general rule, compounded oils are not required in one- and two-stage compressors.

For temperatures below 300° F a 300 S.U.S. at 100° F oil is satisfactory. Higher temperatures will require a 400 to 600 S.U.S. at 100° F oil.

In some cylinders oxidation-inhibited oils have been found helpful, as in an air-cooled compressor cylinder where it is splash-lubricated from the crankcase.

Whether the cylinder is of large or small diameter, these recommendations remain the same.

Oil-Feed Rates

The majority of compressor bearings are splash- or force-feed lubricated. In spite of baffles and stuffing boxes, considerable oil sometimes gets into the cylinders from the piston rod. This is especially true of compressors with mechanical unloaders running under part capacity. Some air compressors where oil-free air is required run on carbon rings and require only one drop of oil every 20 minutes to lubricate the valves.

The table given here is a guide to suitable grades and oil-feed rates for single and two-stage air-compressor cylinders compressing to 500 pounds per square inch.

SPECIFICATIONS AND OIL-FEED RATES

Saybolt Viscosity at 100° F	*Cylinder Size*	*Drops per Minute*	*Pints per Cylinder 10 Hours*
300	6 × 6	1 to 2	¼
300	12 × 12	2 to 3	½
300	24 × 24	4	¾
300	36 × 36	5	1

Pressures Above 500 Pounds per Square Inch

For three-, four-, and five-stage air compressors and final discharge pressures up to 5000 pounds per square inch, follow the previous chart for approximate oil-feed rates to each cylinder.

Examination of Valves and Piston Rings

The parts in a compressor most in need of periodic inspection are the discharge valves. A specified time cannot be given for this inspection, as dirt in the air, mechanical condition, and design of the unit are all factors in determining deposits. Once deposits start to form, they restrict the air flow, raise the temperature, and increase the rate of deposit formation. Most industrial units can operate a year between inspections. The piston rings should be examined every 3 years, and at that time the edges should be chamfered about $\frac{1}{16}$ to $\frac{1}{8}$ inch to prevent them from acting as scrapers to dislodge the oil film on the cylinder wall.

Air-Compressor Fires

Fires and explosions in air-compressor systems are of comparatively rare occurrence, but there are records of serious mishaps, some of which have caused appreciable damage, or even loss of life. To follow the cause of an explosion is a simple matter, although at first glance the idea sounds incredible.

The great majority of compressors are designed to discharge the air at a temperature below 300° F. Hence at no stage in a compressor system is the air temperature above the flash point of the lightest lubricating oils. Furthermore, the highest discharge temperature prevails for only a small percentage of the piston stroke, and, since the cylinders are equipped with water-cooled jackets or heat-radiating fins, the oil film on the cylinder wall is maintained on a cool surface, which presents no problem in lubrication.

However, consider what happens when the oil-feed rate is excessive, when considerable dust is present in the air, or when the oil is heavy and tacky. Over a period of time any one of these factors, or a combination of them, will tend to produce sticky deposits which build up and slowly harden. If these deposits are allowed to accumulate unchecked in and around the discharge valves, the passages close up by degrees until "wire drawing" of the air ensues, with a resulting rise in the discharge temperature. Should a deposit of this type break off and lodge under the seat of a discharge valve, a percentage of the discharged air will return to the cylinder and be recompressed, thereby accelerating the rise in temperature.

Eventually a condition may be created wherein the lubricating oil is distilled into a highly inflammable vapor which awaits only the spark from a glowing deposit or the hammer blow of a valve to produce ignition. When this occurs, a fire is started inside the system, and, depending upon the ratio of air to vapor, a violent explosion may result. Obviously a situation of this kind is possible only in an extreme case of neglect.

Contrary to any theoretical consideration, there is no advantage in using high-flash-point oils for compressor lubrication. The higher the flash point, the heavier and more unsuitable the oil. When a dangerous condition is created, the cause is due to neglect, against which no oil made will provide insurance.

Vacuum Pumps

The lubrication of a vacuum-pump cylinder exhausting air is not very different from the lubrication of an air-compressor cylinder. However, in some cases of high vacuum it may be found advantageous to use an oil one grade heavier to secure a more tenacious oil film on the cylinder walls under vacuum. Then the viscosity should be about

400 S.U.S. at 100° F. The same oil-feed rates apply as outlined for air-compressor cylinders. Many vacuum pumps and compressors handle many gases other than air. These may effect the lubricant. Special lubricants and application methods are required.

Beverage Compressors

When CO_2 gas is being compressed to charge beverages, the use of an ordinary petroleum oil in compressor cylinders may be prohibitive on account of the taste, and therefore the use of glycerine or a white medicinal-type oil may sometimes be permissible. Although they are not good lubricants in the strict sense of the term, they do prevent wear to some extent. Compressors of this type are often equipped with special piston rings, as, for example, carbon rings, to compensate for the lack of lubrication.

Propane (C_3H_8)

Propane has a high diluting effect on lubricating oils. Here again mineral oils are the best lubricants for compressor-cylinder lubrication. Castor oil must be used when condensation occurs in the cylinder. However, contamination is often a factor and then light-bodied, light-colored grades are generally employed in sparing quantity, particularly where the liquid is sold in bottles for domestic gas burners.

Natural Gases

Diluting Gases

For compressors pumping natural gas that is "dry" no problem is involved, and the cylinder oil requirements are the same as for air compressors. For "wet" gases heavier lubricating oils are necessary to allow for the diluting and washing effect of the suspended liquids. In such cases the addition of 5 to 10 per cent of compounding in the form of tallow or lard oil will be found effective in setting up resistance against dislodgment of the oil film from the cylinder walls. Where water is present, the addition of 10 to 20 per cent of rapeseed oil will be found advantageous.

The estimate of lubricating oil viscosity or body for a particular wet gas pumping operation is generally a matter of trial and error, which, however, may be based on the rough approximation that 5 per cent of kerosene will reduce the viscosity of a medium-bodied oil down to 300 S.U.S. and a dilution of 10 per cent will reduce the viscosity from 450 S.U.S. to 300 S.U.S.

In operations involving wet gases with high solvency power the use of a highly filtered, compounded steam-cylinder oil may be required. This question is best answered by periodic examination of the cylinder walls and discharge valves. If the cylinder walls show a coating of oil when wiped with a piece of cigarette paper and the valves are just moist with oil, the compressor is receiving the proper type of oil and rate of feed.

Oxygen Compressors

Since oxygen is a highly active element, petroleum lubricants are unsafe to use in compressors pumping this gas on account of the fire and explosion hazard. The best that can be done is to use distilled water or a soap and water solution as a lubricant. However, the soap must not contain saponifiable matter.

Hydrogen, Nitrogen, Argon, Helium

These gases are inactive in the presence of petroleum oils, and for compressor lubrication the service is the same as for air compressors. However, if a pure gas is required, distilled water is generally used as a lubricant.

Chlorine

Since this element is highly active in the presence of petroleum oils, they cannot be used with chlorine.

Acetylene

Petroleum oils are suitable for the lubrication of compressor cylinders pumping acetylene gas. However, the compressor system should be adequately equipped with separators in the discharge line to prevent the oil from getting into the lines, where its presence is detrimental in the commercial product. Turbine-grade oils having a viscosity of 300 to 400 seconds at 100° F are commonly used for cylinder lubrication.

Producer, Water, and Coke-Oven Gases

If the above gases are scrubbed clean, the compressor cylinders are not difficult to lubricate and may be regarded as similar to air compressors insofar as recommendations apply. However, compounded oils containing a small percentage of fatty oil are generally required when the gas contains tarry materials, and particularly if liquid solvents are present.

25

Pneumatic Tools

Pneumatic tools comprise air hammers, drills, stopers, drifters, and a great variety of machines operated by air under pressure. These tools are actuated by small reciprocating pistons wherever a hammer-like motion is required. If a rotating motion is required, a vane-type mechanism is applied which makes use of air pressure to create power. Hence the operating principle is similar to a reciprocating steam or internal-combustion engine.

Considerable trouble is sometimes experienced with these machines owing to the use of lubricants that are not suitable for the operating conditions. In the first place, the air delivered to a pneumatic tool is generally at room or atmospheric temperature, and during its expansion in the cylinders a drop in temperature takes place; hence the first consideration is to use light oils that will not congeal or soft greases that will not thicken, depending upon the method of lubrication of the machine. In the second place, there is generally some water present in the compressed air; therefore a small percentage of rapeseed oil compounding is advantageous to produce a slight emulsion. This action retards the washing-out effect which water exerts on straight mineral oils.

Rapeseed oil is an excellent emulsifying agent in the presence of cold or warm water; consequently it is used extensively in marine-engine oils. However, marine-engine oils are much too viscous for pneumatic tool mechanisms because the lightest grades generally have a viscosity rating of about 500 S.U.S., which is too heavy for comparatively small pistons operating on cool or slightly warm air. Owing to the fact that rapeseed oil, particularly blown rapeseed, is a comparatively viscous product, only a small amount can be used in a mineral oil adapted to the lubrication of pneumatic tools, generally not more than 10 per cent. The operating conditions of pneumatic tools are such that even during the summer a 300 S.U.S. oil is heavy enough for the largest machines, and with 5 per cent of rape the air cylinders are assured an effective oil film.

Another important factor in pneumatic tool operation is air temperature. When air functions in the cylinders of these machines it does work, and therefore drops proportionately in temperature, thus producing a refrigerating effect. In fact, ice formations are a common sight on the exhaust ports of pneumatic tools. This feature depends to a large extent upon the initial temperature of the air supply, but for cold-weather operation it is often necessary to use a light ice-machine oil having a Saybolt viscosity rating below 100 S.U.S. and a pour point of −20° F.

Air Heaters

When compressed air is subjected to freezing temperatures in the air lines, the most satisfactory method of overcoming operating and lubricating difficulties is to install heating facilities. These units are designed for oil firing, coal firing, etc., depending upon the most suitable heating medium available at a particular location.

Line Oilers

Line oilers are designed to feed oil directly into the air lines. If the flow of air is sufficiently rapid, they act as atomizers to break up the oil into a fine mist. This method is very effective, but the oilers must be moved up near the machines as the pneumatic tools advance. For example, in tunnel drilling jobs the air lines are extended as boring progresses, but if the line oilers are not advanced at the same time, the oil tends to settle out in the hosing and eventually reaches the machines in the form of intermittent slugs which slow up and sometimes stop the pistons. Under similar circumstances, marine-engine oils often emulsify in the lines and reach the machines in heavy liver-like streamers which are even more objectionable.

Manufacturers of pneumatic tools generally issue specifications covering suitable types of oils and greases for their machines. Sometimes these instructions are rather technical and complicated because they vary for different designs and makes. As a general rule it is not practical to carry more than two grades of lubricants on hand at one time when operating a number of pneumatic tools.

Grease Lubrication

Grease is sometimes used to lubricate the gears of air tools. For low temperatures a lime or lithium soap-base grease, about 300 penetration, embodying a low pour point oil, should be used.

Rust Prevention for Pneumatic Tools

When pneumatic tools are not in use, and particularly when they are placed in storage, an oil containing an antirust compound should be used liberally to slush all the internal parts. This type of oil is also recommended for normal lubricating purposes, but for storage purposes the grade should be heavier, as, for example, Saybolt viscosity reading of about 300 to 600 seconds at 100° F.

Dirt

Dirt coming from pipes and hoses and that resulting from connecting and disconnecting the tool finds its way into the working parts of air tools. Suitable strainers or filters are useful in minimizing this difficulty.

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Refrigerating Machines

The design of a refrigerating compressor is not very different from the design of an air compressor; in fact, it is fundamentally the same for most applications. Under the following headings the various problems encountered in lubricating refrigerating machines are discussed.

Ammonia (NH_3) Refrigerating Compressors

At room temperature and pressure ammonia gas is slightly soluble in well-refined straight mineral oils, but it has no chemical effect. With increased pressure the solubility increases, and with increased temperature the solubility decreases. The lubrication of ammonia refrigerating compressors is a simple matter, but there are occasions when operating difficulties arise, with troublesome consequences. These problems are discussed under the headings which follow.

Cylinder Wall and Discharge Temperatures

The cylinder walls of an ammonia refrigerating compressor are in direct contact with low-temperature suction gas and moderate-temperature discharge gas, while externally they are water cooled. As a result of these conditions the oil film on a cylinder wall is seldom subjected to temperatures above 170° F. However, discharge valves operate under higher temperatures, generally between 200 and 250° F, and for this reason they should be examined and cleaned every 6 months. Piston rings should be examined every 3 years, and, if they are found in satisfactory condition for continued service, the sharp edges should be chamfered slightly to prevent their dislodging the oil film.

Excessive Discharge Temperatures

High discharge temperatures are a sure sign that the compressor is doing useless work. The cause is generally mechanical, as, for example, dirty condenser tubes or clogged piping. Under these circumstances the excess heat tends to produce and bake gummy deposits of oil and dirt on the discharge valves and in the nearby passages, which accelerates the condition. High discharge temperatures are likely to occur when operating against high head pressures, but this condition is sometimes unavoidable.

Disappearance of the Oil Charge

Sudden disappearance of the oil charge occasionally takes place in the trunk-piston type of refrigerating machines operating on variable-back pressures. With a sudden drop in back pressure the absorbed ammonia in the crankcase oil is released in excessive volume; the resulting ebullition of froth is picked up by the pistons in appreciable quantity; and the oil is delivered into the high-pressure side of the system.

This type of frothing can be avoided by changing the back pressure gradually. The use of a heavier-bodied oil is sometimes thought to be a solution of this problem, but this is not so. The heavier the oil the more gas it will absorb under pressure, and the problem is only aggravated.

Water in the crankcase will also produce this hazard by forming ammonium hydroxide, which has emulsifying properties in the presence of lubricating oils.

Worn piston and oil-scraper rings may also cause an excessive oil loss in trunk-piston refrigerating machines by allowing too much of the splashed oil to pass into the discharge line. In similar manner excessive gas leakage passing a piston admits high-pressure gas to the crankcase, and while this gas is bypassed to the suction line it may carry oil spray, which eventually passes out through the discharge valves.

In large systems, operating with a −50° F suction and a +270° F discharge, the oil carryover from the bearing system, which leaks past the piston rod because of the vacuum in the low-pressure cylinder on the suction stroke, may be a factor.

Deposits in Cooling Coils

Refrigerating oils should have pour points below 0° F. If deposits accumulate in the coils, either the pour point is not low enough for the oil to drain at the traps or an excessive quantity is being fed into the cylinders. In the event that deposits are present throughout the system and steam is required to dislodge and melt them, great care must be exercised to drain the coils dry. Otherwise expansion valves will block with ice, and crankcase oil will emulsify owing to the formation of ammonium hydroxide.

Recommendations and Oil-Feed Rates

Naphthenic-type oils are considered best adapted to ammonia refrigerating-machine service for the reason that they are easily dewaxed and have normally low pour points. The chart given below is a guide to average oil-feed rates when the cylinders and stuffing boxes are supplied by means of a mechanical lubricator. The same oil should of course be used in the crankcase, because oil tends to enter the compressor from the piston rod.

S.A.E. No.	*Cylinder Size in Inches*	*Saybolt Viscosity at 100° F*	*Pour Point °F Average* *	*Drops per Minute*	*Pints per 10 Hours*
. .	Small units	115 to 150	−20	Splash	Splash
10	10 × 10	200	−15	4	¾
10	12 × 18	200	−15	5	1
10 to 20	15 × 22	200 to 300	−15	7	1 plus

* As a general rule the pour point of the oil should be below the temperature carried in the system.

Carbon Dioxide (CO_2) Compressors

Carbon Dioxide (CO_2) Refrigerating Machines

At room temperature and pressure carbon dioxide gas is slightly soluble in petroleum lubricating oils, but it has no chemical effect. Hence the lubricating oil requirements of a carbon dioxide refrigerating compressor are the same as for an ammonia compressor.

Dry Ice Compressors, Carbon Dioxide (CO_2)

In manufacturing Dry Ice from carbon dioxide gas there are different opinions on the subject of compressor-cylinder lubrication, but the most effective and satisfactory lubricant for the majority of installations is a turbine grade of oil having a Saybolt viscosity of about 300 seconds at 100° F (S.A.E. 20). When this type of oil is fed into the cylinders by means of a mechanical lubricator, the supply can be controlled to a point where oil contamination is negligible in the commercial product. The oil-film strength on cylinder walls is very superior when compared with that provided by white oils, even allowing for a higher permissible oil-feed rate with the latter type. With effective trapping equipment, no trouble from oil contamination should occur with an S.A.E. 20 turbine grade of oil in service.

Freon (CCl_2F_2) Refrigerating Compressors

"Freon" is miscible with oil, particularly when the two are under pressure.

Insofar as lubrication is concerned, the primary effect of absorption is a reduction in viscosity of the oil. The two tables show the effect of various percentages of liquid Freon upon the viscosity of two mineral oils.

OIL, 325 SECONDS SAYBOLT VISCOSITY AT 100° F

Per Cent Liquid Freon in Oil by Weight	*Viscosity of Mixture at*			
	60° F	*100° F*	*140° F*	*180° F*
0	1400	325	120	66
5	640	190	84	53
10	335	120	65	47
20	120	64	46	39
30	68	46	39	..

OIL, 150 SECONDS SAYBOLT VISCOSITY AT 100° F

Per Cent Liquid Freon in Oil by Weight	*Viscosity of Mixture at*			
	60° F	*100° F*	*140° F*	*180° F*
0	460	150	72	50
5	160	80	53	43
10	105	62	47	40
20	56	44	39	..
30	42	37	..	..

Oil viscosity has some effect upon the miscibility of Freon because the higher-viscosity oils absorb and retain a greater percentage of this refrigerant. Also, increasing the pressure or decreasing the temperature will increase the amount of Freon which may be absorbed by the oil.

Because of the effect of Freon on oil viscosity, a more viscous lubricating oil is usually necessary with it than would be used with ammonia or carbon dioxide. Care should be taken to exclude water because any moisture present will freeze out and restrict the flow of refrigerant through the regulating valve.

The type of compressor as well as the design of the system and quantity of Freon therein influences the degree to which the viscosity of the lubricating oil will be reduced by admixture with Freon. For some small enclosed household units, an oil having a viscosity of 150 seconds Saybolt at 100° F is satisfactory, but for larger air-conditioning compressors of the reciprocating type, oils as viscous as 900 seconds at 100° F are used. In a centrifugal type of compressor only the bearings require lubrication. A 300 S.S.U. at 100° F is used, as dilution will thin it down, depending on operating loads.

For low-temperature operation a low pour point oil should be specified. Oil carried over into the gas system is deposited on the evaporator coils and should be able to drain freely. Bearing temperatures may run as high as 200° F, so that an oxidation-inhibited oil is recommended.

Sulfur Dioxide (SO_2) Refrigerating Compressors

In contact with liquid sulfur dioxide, lubricating oils are soluble in amounts up to about 40 per cent of the oil charge. Technical white oils are least soluble and average about 25 per cent of the oil charge. Sulfur dioxide is an active refining agent and will dissolve out any unsaturated hydrocarbons in lubricating oils. Hence, white oils are commonly employed in the compressor systems of hermetically sealed household refrigerating units for the reason that white oils are treated with sulfuric acid and repeated washings with caustic soda and water and are then filtered through fuller's earth until they become colorless, odorless, tasteless, and free from aromatic compounds and unsaturated hydrocarbons. For larger machines, the film strength of a white oil is not sufficient to lubricate compressor cylinders, and well-refined lubricating oils of light straw color are employed on account of their superior lubricating value.

Methyl Chloride (CH_3Cl) and Ethyl Chloride (CH_5Cl)

These two refrigerants have a high diluting effect on lubricating oils. However, mineral oils are the best lubricants for compressor cylinders handling these gases. Saybolt viscosities range from 200 seconds at 100° F to 900 seconds at 100° F, depending on the design and size of the compressor. The lubricating oil requirements are very similar to those of machines using Freon.

PROPERTIES OF COMMON COMMERCIAL REFRIGERANTS

Refrigerant	Chemical Symbol	Hazard Factors				Thermal Factors								Operating Factors				
		Safety Code Group*	Irritant?	Inflammable?	Concentration in Air to Form Explosive Mixture	Condensing Pressure, 86° F, Psi Abs	Evaporation Pressure, 5° F, Psi Abs	Boiling Point, °F (Atmospheric)	Freezing Point, °F (Atmospheric)	Critical Temperature, °F	Net Refrigeration Effect (86—5° F), Btu per Lb	Refrigerant Handled, Lb per Min per Ton	Piston Displacement, Cu Ft per Min per Ton	React Harmfully with Lubricating Oils?	Mix with Lube Oil?	Corrosive to Metals? (Alone)	Corrosive to Metals? (With Water)	Materials Spoiled by Exposure to Refrigerant
Ammonia	NH_3	2	Yes	Slightly	13–27	169.2	34.3	−28	−107.9	271.2	474.4	0.4	3.4	No	No	No[1]	Copper, alloys	Foods, textiles
Carbon dioxide	Co_2	1	No	No	None	1039.0	334.4	−108.4	−69.9	87.8	55.0	3.6	0.94	No	No	No	Iron, copper[2]	None
Carrene—1 (Dichloromethane)	CH_2Cl_2	1	No	No	None	10.6	1.17	105	−142.0	421.0	134.6	1.5	74.5	No	Yes	No	No	. . .
Carrene—2 (Freon—11) (Trichloromonofluoromethane)	CCl_3F	1	No	No	None	18.3	3.0	74.7	−168.0	388.4	67.5	3.0	36.3	No	Yes	No	No	None
Freon—12 (Dichlorodifluoromethane)	CCl_2F_2	1	No	No	None	107.9	26.6	−21.7	−247.0	233.0	51.1	3.9	5.8	No	Yes	No	No	None
Freon—21 (Dichloromonofluoromethane)	$CHCl_2F$	1	No	Slightly	None	31.2	5.3	48.0	−196.6	353.3	89.4	2.2	20.4	No	Yes	No	No	None
Dielene (Dichloroethylene)	$C_2H_2Cl_2$	2	[3]	. . .	5–11	6.9	0.82	122	−70.0	470.0	114.4	1.75	112.6	. . .	Yes	. . .	. . .	. . .
Ethyl chloride	C_2H_5Cl	2	[3]	Yes	4–14	27.1	4.7	54.0	−217.7	369.0	142.9	1.4	22.6	. . .	Yes	. . .	. . .	. . .
Isobutane	$(CH_3)_3CH$	3	[4]	Yes	2–6	59.5	13.1	10.3	−229.0	272.7	111.5	1.8	11.5	No	Yes	No	No	. . .
Methyl chloride	CH_3Cl	2	No[3]	Slightly	8–17	95.5	20.9	−10.7	−144.0	289.6	148.7	1.3	6.1	No	Yes	No	Zinc, alum	None
Sulfur dioxide	SO_2	2	Yes	No	None	66.5	11.8	14.0	−98.9	314.8	143.1	1.4	9.1	Some	No	No	Most metals	Flowers, some dyes
Water	H_2O	[5]	No	No	None	0.62	0.02	212	32	706.0	1007.3	0.2	2288.0	No	No	Yes	. . .	None

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* American Standard Safety Code for Mechanical Refrigeration divides refrigerants into three groups: Group 1 may be used, with minor limitations, in institutional, public assembly, residential, commercial, and industrial occupancies; Group 2 may be used, with strict limitations, in the same occupancies; Group 3 may be used only in residential, commercial, and industrial occupancies, in unit systems containing not more than 6 pounds.

[1] Pure anhydrous ammonia attacks copper but in actual practice seems to give no trouble.

[2] Action continues only when oxygen is present.

[3] Considered anesthetic.

[4] Underwriters recommend adding odorant such as spearmint.

[5] Code does not list water as refrigerant, but it is probably safest.

BOILING POINTS OF AMMONIA AND CARBON DIOXIDE AT VARIOUS PRESSURES

Gage pressure (based on standard atmospheric pressure at sea level of 14.7 psi) corresponding to various boiling temperatures.

British Units			*Metric Units*		
	Gage Pressure, psi			*Gage Pressure, kg per sq cm*	
Boiling Temperature, °F	*Ammonia* (NH_3)	*Carbon Dioxide* (CO_2)	*Boiling Temperature, °C*	*Ammonia* (NH_3)	*Carbon Dioxide* (CO_2)
110	232.3	..	43.3	16.33	..
100	197.2	..	37.7	13.87	..
90	165.9	..	32.2	11.66	..
87.8[1]	159.5	1051	31.0	11.21	73.9
86	154.5	1027	30.0	10.86	72.2
80	138.3	953	26.6	9.72	67.0
70	114.1	838	21.1	8.02	58.9
60	92.9	734	15.5	6.53	51.8
50	74.5	639	10.0	5.24	44.9
40	58.6	553	4.4	4.12	38.9
30	45.0	476	−1.1	3.16	33.5
20	33.5	408	−6.6	2.36	28.7
10	23.8	345	−12.2	1.67	24.3
5	19.6	316	−15.0	1.38	22.2
0	15.7	290	−17.7	1.10	20.4
−10	9.0	242	−23.3	0.63	17.0
−20	3.6	200	−28.8	0.25	14.1
−28	0.0	170	−33.3	0.00	12.0
−30	13.9[2]	163	−34.4	0.98[2]	11.5
−40	10.4	131	−40.0	0.73	9.2
−50	7.67	103	−45.5	0.539	7.24
−60	5.55	79.3	−51.1	0.390	5.57
−69.9	3.96	60.4[3]	−56.6	0.278	4.25
−107.9	0.88[3]	0.8	−77.7	0.062	0.56
−109.3		0	−78.5		0.00

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[1] The temperature of 87.8° F (31.0° C) is called the critical temperature of carbon dioxide because above this temperature it cannot be converted to a liquid by any pressure, however great. Every liquefiable vapor has such a critical temperature, that for ammonia being 271.4° F (133° C).

[2] Pressures less than atmospheric are given in pounds per square inches or kilograms per square centimeter absolute.

[3] The triple point of NH_3 is at −107.9° F and 0.88 psi absolute pressure. That of CO_2 is −69.9° F and 60.4 lb gage. Below the triple-point temperature the liquid phase does not exist, the substance passing directly from vapor to solid state when heat is removed; and from solid to vapor when heat is added, so long as the indicated triple-point pressure and temperature are not exceeded.

27

Reduction Gears

The most difficult problem encountered in the field of reduction gear lubrication is to determine the cause of wear or failure when examining a damaged gear. Very often gear failures are caused by conditions beyond the control of commercial lubricants, but there are also occasions when steps may be taken to correct the fault, either by changing the type of lubricant or by making mechanical alterations, such as installing facilities to lower the temperature of oil.

Gear designs are based on established and well-tried formulas, and the great majority of units operate with remarkable efficiency and reliability. However, there are many operating features which are not understood, and for that reason they are classed as phenomena. Before discussing gear lubrication it is very helpful to possess some knowledge of the metallurgical factors which have a direct influence on gear operation.

Probably the most difficult study is that of metal fatigue and consequent breakdown of the metal skin which sometimes occurs on the surface of gear teeth. This condition results in various forms of wear which must be diagnosed to determine the actual cause. In this connection it is interesting to know that many metals will not work well together and form a team. The following are a few examples of gear design phenomena.

Steel that has been hardened by oil does not always operate well with steel that has been case-hardened; hardened nickel steels do not always operate well together, particularly when appreciable heat exists; bronze will operate with cast iron and hardened steel but not with soft steel; soft steel will operate well with cast iron, soft brasses, and sometimes with hardened steel but not with bronze or soft steel against soft steel; cast iron generally operates well with all other metals; hardened steel will work well with soft steel, and so on. The explanation of these various combinations is probably bound up in the phenomenon of lubrication, but the choice of metals that will operate well together in a particular type of reduction gear is based on practical data that have been secured by trial and error methods over a period of years.

Another feature about which little is known is that of shock loads on gear teeth. Here again the precedent is set by experience. For example, automobile transmissions, rear axles, and steering gears have been standardized to a large extent by many years of experience on roads that are reasonably smooth. When the same type of equipment is used on rough roads, or no roads at all, it will break down and generally end up beyond repair in a comparatively short time. The extent of the dynamic, or shock, loads that may be anticipated under various operating conditions is an extremely difficult matter to gage.

Vibrations are still another source of difficulty in some gear applications, and mathematical calculations are rendered difficult by the many factors which enter into this phase of gear operation. However, high-frequency vibration will destroy gear teeth irrespective of the lubricant. Then an analysis of the system must be made. Sometimes it is possible to run above or below the critical speed. In other cases it is necessary to change the system.

Last but not least, there are the physical limitations of available lubricating oils. While considerable progress has been made in the science of adding materials to mineral oils to increase their load-carrying properties to an almost phenomenal extent, the fact remains that all these compounded oils contain ingredients that are less stable than the mineral oil, and most industrial reduction gears are therefore lubricated by straight mineral oils.

Gear Designs

There are many gear designs adapted to the transmission of power, but the standard type of gear tooth is the involute design which is shown in the accompanying diagrams. In all designs the speed ratios are controlled by the relative number of teeth in each gear, and the small driving gear is known as the **pinion.**

Figure 1 illustrates some of the terms used in connection with gears. The circular pitch is the distance from one point on a tooth to a corresponding point on the next tooth. The pitch circles represent the diameters of smooth cylinders in rolling contact. The pitch circle is the basic line from which the calculations are made for the number and shape of teeth. The portion of contact surface above the pitch circle of gear teeth is known as the face, and the portion below the pitch circle is known as the flank.

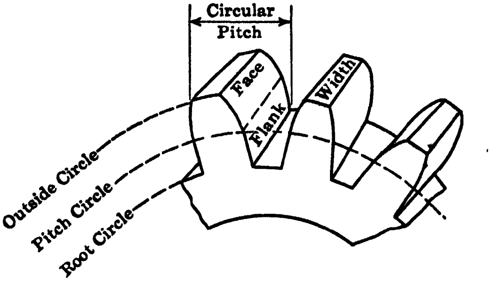

FIG. 1. Terms used in gear design.

Spur Gears

Spur gears have teeth formed upon the surfaces of cylinders. They are mostly of the involute type shown in Fig. 1. This design is termed a straight spur gear.

Helical Gears

Helical gears have their teeth wound around the surface of cylinders, as shown in Fig. 2. This type of gear is more difficult to cut than a spur gear but has the advantage of providing a larger contact surface. Gear teeth deflect with load, and, although the amount is small, the result produces a nonuniform transmission of power. Hence, in large gears transmitting considerable horsepower, the contact area is made as liberal as possible. Helical gears cause a definite end thrust which must be taken care of by a thrust bearing. Large horsepowers are generally transmitted by a double set of helicals, one left hand and the other right hand, to balance this thrust.

FIG. 2. Helical gears and pinions. (*Courtesy Foote Bros. Gear and Machine Corp.*)

Herringbone Gears

Herringbone gears are double helical or double spur gears which have their teeth in V-shape formation, as shown in Fig. 3. As with single helical designs, the object is to provide maximum contact area between the teeth.

Bevel Gears

Bevel gears are formed on conical surfaces and transmit power at an angle of 90 degrees. When the teeth are of the helical type, the gear is known as a spiral bevel. The type illustrated in Fig. 4 is straight tooth.

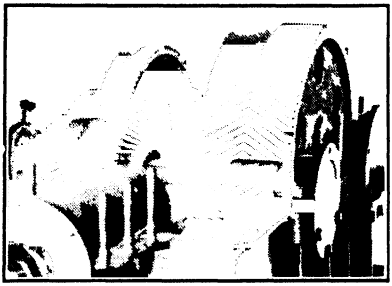

FIG. 3. Herringbone gears and pinions. The gear in the middle is a bevel gear. (*Courtesy Farrel-Birmingham Co , Inc.*)

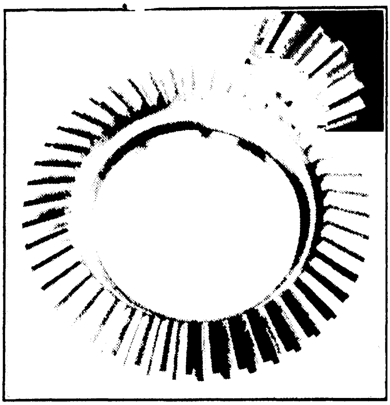

FIG 4. Straight-tooth bevel gear. (*Courtesy Gleason Works.*)

Worm Gears

Worm gears consist of a worm in which the teeth are wound around a cylindrical surface. This worm meshes with a gear wheel which has specially cut teeth that make contact with the worm (see Fig. 5). The main advantage of this design is the high reduction ratios that may be secured with a small unit.

Hypoid Gears

Hypoid gears differ from bevel gears in that the axes of the shafts are not in the same plane (see Fig. 6). The pinion shaft is below the gear shaft, and extensions of the two shafts would not meet as in the spiral bevel design. Hypoid gears were developed for automotive rear end drives as a matter of convenience in lowering the drive shaft below the floor boards. For similar reasons of space requirements this type of gear is sometimes adapted to industrial installations, where a lower drive shaft is a matter of convenience.

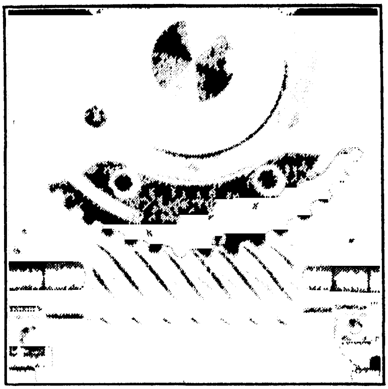

FIG 5. Worm gear. (*Courtesy Cleveland Worm and Gear Co.*)

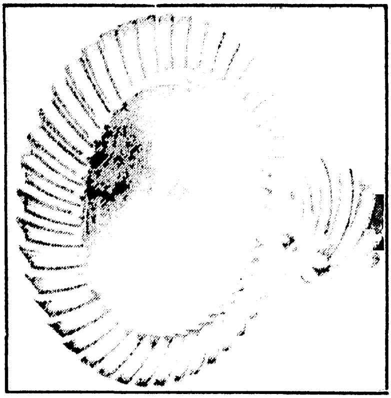

FIG. 6 Hypoid gear. Notice that the pinion is below the center line of the gear wheel. (*Courtesy Gleason Works.*)

Motion and Contact Areas of Gear Teeth

The action of gear teeth is a combination of sliding and rolling motion. Figure 7 shows the outline of a spur gear in three positions. In position *A* the teeth are just commencing to mesh, and sliding motion is at a maximum. In position *B* the teeth are making contact at the pitch line, where pure rolling motion occurs. In position *C* the teeth are disengaging, and sliding motion is again at a maximum. Between these three positions, the teeth are in various stages of combined rolling and sliding action, with the percentage of rolling motion greatest at the pitch line and least at the points of engagement and disengagement.

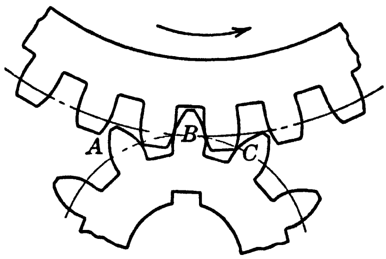

FIG. 7. Sliding and rolling action of gear teeth.

In Chapter 15 on plain bearing lubrication, it was pointed out that, in order to maintain fluid film lubrication, there must be sliding contact and the opposing surfaces must be at an angle to permit the building up of an oil wedge. These conditions are fulfilled when two gear teeth are in contact and sliding motion is in effect. However, contact along the pitch line is pure rolling motion which is not favorable for oil film maintenance because there is no sliding action to build up an oil wedge.

As might be expected, metal fatigue and consequent pitting of gear teeth generally take place on the smaller pinion just before the pitch line on the flank of the tooth faces. This is due to the fact that in this area sliding motion is liable to be insufficient to produce an effective oil wedge action when the speed is low or when shock loads are excessive. Thus metal-to-metal contact may occur which sooner or later produces metal fatigue, and little pieces of metal drop out, leaving holes or pits.

When gears are turning without transmitting power the meshing teeth may be considered to make line contact only, but when power is being transmitted, the teeth deflect under pressure and line contact becomes area contact. In small gears the width of contact across the face of gear teeth may average $1/64$ to $3/16$ of an inch for very large heavy-duty gears.

In gear designs the stresses and strains are calculated from established formulas, and, assuming that a spur gear is 30 inches in diameter and loaded to 3000 pounds per inch line of face, the width of the contact area between two teeth will be approximately 0.05 inch under load pressures. The compressive stress in the middle of this contact area will be 80,000 psi, and ordinary gear steels of 200 Brinell hardness will carry this load without difficulty when supplied with a suitable type of oil adapted to the particular speed.

Heavy-duty steel mill gears are sometimes designed to carry a load of 10,000 pounds per inch line of contact face on the meshing teeth, and sometimes the use of an extreme-pressure oil is necessary to meet the high unit pressures on gear teeth designed for these high pressures. However, the majority of reduction gears are easily lubricated by straight mineral oils.

Gear Loads and Hydraulic Oil Pressures

Reduction gear teeth carry much higher unit pressures than plain bearings, a condition which is sometimes difficult to understand at first glance. Based on readings taken from various laboratory testing machines which measure the load-carrying ability of mineral oils at various speeds in plain bearings, the average breakdown point of a straight mineral oil film occurs between 2000 and 5000 pounds pressure to the square inch when the temperature is 100° F. However, in a reduction gear, the unit pressure is generally far beyond the ordinary breakdown point of oil films in plain bearings, and 80,000 pounds per square inch might be considered a moderate operating pressure between the contact areas of a common spur gear.

This operating difference is due to the fact that, in a reduction gear turning at moderate to high speed, the oil film is subjected to a sudden hydraulic pressure, and, before it has time to escape from the sides of the teeth, the particular area of contact is no longer in mesh.

With high speeds, hard steels, and a continuous flood of cool oil pouring onto the meshing teeth, the hydraulic pressures resulting from shock loads may safely reach 250,000 psi on oil films between the contact areas, and this without causing damage. In fact, shock load pressures in the vicinity of 400,000 psi have been measured on the surface of hypoid gears in automobile transmissions. This type of transmission is poorly adapted to carry high pressures, and for this reason specially compounded lubricants are used in the gear housings. Nevertheless, hydraulic pressures of this order are sustained by oil films between gear teeth, and metal-to-metal contact is actually prevented. With sufficient speed to prevent the oil film from escaping and with a flood of cool oil to the contact areas, the gear teeth may actually break off before metal-to-metal contact is allowed. In practice this sometimes happens, as, for example, when transmissions are subjected to severe shock loads which are beyond the strength of the materials used.

The viscosity range of lubricants employed on reduction gears varies with the speed, load, and method of applying the lubricant. For example, single-reduction marine turbine gears generally require an oil having a viscosity of about 300 to 450 seconds Saybolt at 100° F (S.A.E. 20 to 30). Most turbine shafts and the gear pinions thereon revolve at speeds of 1500 to 3600 rpm, and since the oil is sprayed into the meshing teeth by means of jets and then returned to a cooler, the usual recommendation is a comparatively light oil. In actual operation this type of oil is fluid and quick-acting, dissipates heat readily, and reduces the effect of fluid friction which occurs within the oil itself to raise the operating temperature.

In fast-moving gears the teeth act as their own pumps to throw oil into the contact areas and, as long as the supply is sufficient on the gear teeth, this automatic action will maintain a constant oil wedge in front of the meshing areas. This automatic action is very similar to that produced by a revolving shaft in a bearing. However, oil-wedge production decreases as speed decreases, and, in addition, the time of contact between gear teeth increases. This latter condition gives the oil film more time to escape under hydraulic pressure. Consequently, heavily loaded low-speed gears require viscous, tacky oils to overcome these deficiencies and prevent metal-to-metal contact of the teeth.

Influence of Gear Efficiencies

In actual practice, precision gears may have efficiencies of 99 per cent, and on large turbine reductions this figure is sometimes exceeded.

These high mechanical efficiencies and load-carrying abilities of gear teeth may be explained by assuming that a journal revolving in a bearing represents 100 per cent sliding motion and 100 per cent contact time between the journal and bearing. On gear teeth the time of sliding contact in any particular area of two meshing teeth is only a fraction of a second and many range from 0 (rolling motion, which is theoretically frictionless) to almost 100 per cent sliding action. Hence the unit pressures on the teeth can be much greater than in a bearing, and this theoretical consideration is substantiated in practice.

In gears having few teeth the lengths of the involute curves are relatively greater, a feature which increases sliding action. This explains why worm and hypoid gears are less efficient than other types for the same duty. They approach the action of a journal revolving in a bearing. Consequently, heavier oils must be used, generally viscous mineral oils containing compounds that increase the load-carrying properties of the oil films.

The action of spur and herringbone gears is composed of about 50 per cent sliding and 50 per cent rolling motion, and with precision gears the rolling action is higher. In worm and hypoid gears the rolling action is generally less than 10 per cent, the rest being sliding action.

Heat generated by the fluid friction of oil films depends largely upon the pressure, relative sliding velocity, and time of contact between the mating surfaces. These conditions influence gear efficiency. For example, if a gear transmitting 1000 horsepower has a mechanical efficiency of 99 per cent, there will be a 1 per cent loss which is converted into heat. This 1 per cent represents 10 horsepower, which in turn is equivalent to nearly 425 British thermal units per minute, and most of this heat is absorbed by the oil. When the housing is not large enough to reasonably dissipate the heat generated therein, the oil must be cooled by additional methods, such as a circulating oiling system equipped with an oil cooler, wherein cold water passes through tubes and hot oil passes over the tubes, or else a large tank must be employed where the oil may cool while at rest.

As a general rule, reduction gears transmitting more than 100 horsepower are lubricated by a circulating oiling system for the reason that the housing is not large enough to dissipate the heat generated therein.

Figure 8 shows the average efficiency of a worm gear at various ratios of reduction. At high ratios this type of gear is not as efficient as spur and herringbone designs but has the advantage of small size for high ratios.

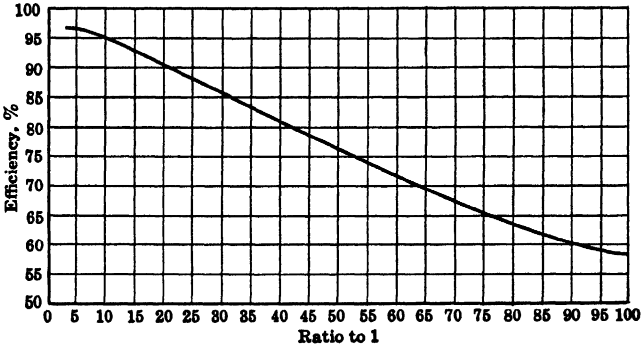

FIG. 8. Worm gear efficiency by ratio of reduction.

Compounded Gear Oils

When it is desired to impart mild extreme-pressure properties to a mineral oil, the most common ingredients are tallow oil or lard oil. These materials have very good resistance against the natural process of oxidation. They also have high flash points equal to that of viscous cylinder stocks.

The most common ratio is 5 per cent of tallow or lard oil for heavy-duty splash-lubricated gears of the worm type. When relative sliding is increased, as in worm gears, the unit pressure must be decreased, or moderate extreme-pressure properties imparted to the mineral oil. This is accomplished very nicely by 5 per cent of animal oil. More than this amount will accomplish no useful purpose but will increase the tendency of rancidity and breakdown of the animal oil owing to oxidation. Incidentally, to improve the oil-wedge action on worm gear faces, manufacturers chamfer the leading edges of the teeth on the driven wheel.

Extreme-Pressure Oils

Extreme-pressure oils are universally manufactured in S.A.E. ratings of 80, 90, 140, and 250 but may be procured in any other desired S.A.E. rating.

The principle of using sulfur, chlorine compounds, phosphorus compounds, etc., has long been known as a "cure" for hot bearings, and the beneficial cooling effect of these elements in metal-cutting operations has also been known for a long time. The art is to incorporate one or more of these basic elements into mineral oils so that they will remain dormant and not react chemically until required. This is accomplished by various chemical formulas wherein compounds of the above-mentioned materials are dispersed in mineral oils.

When metallic friction occurs under pressure between two gear teeth, the intense local heat is sometimes sufficient to cause welding actions which tear the metal and destroy the surfaces. When an antiflux is introduced, the chemical reaction occurring at high temperature forms metallic oxides which prevent the two parts from welding together. This is the principle of all extreme-pressure lubricants. The ingredients might be termed "high-temperature lubricants" because they react to produce a beneficial chemical compound which prevents destructive metallic contact. For example, when sulfur is the chief constituent in the mineral oil, the reaction produces smooth microscopic films of iron sulfide which act as a metallic lubricant to prevent destructive wear when high temperatures occur owing to metal contact. In similar manner iron chloride is formed when the ingredient in the mineral oil is a chlorine compound. Iron phosphide is formed when the ingredient is a phosphorus compound, and so on.

Hypoid gears present a special problem in gear lubrication, and many special lubricants have been developed for this particular application. The relative sliding and rubbing action between the teeth is greatly increased by the off-center position of the pinion shaft, and compounds which react chemically at high temperatures are employed to prevent metal-to-metal contact under these severe operating conditions.

Hypoid gear oils and similar types of lubricants are known as "extreme-pressure lubricants," "E.P. lubricants," etc., and hundreds of patents have been issued on different manufacturing formulas. Hence it would be impracticable to attempt a discussion of the various methods employed to manufacture these products. However, the most common elementary ingredients are sulfur, phosphorus, chlorine, and lead.

These materials, in various forms and combinations, are manufactured into compounds which will disperse uniformly in mineral oils and provide the necessary antiflux or chemical reaction when extreme pressures cause a break in the oil film. Since the aforementioned elements are generally compounded with an animal, vegetable, or fish oil before being mixed with mineral oils, the normal load-carrying ability of the mineral oil is further increased by the presence of the fatty oil. For example, sulfur may be compounded with lard oil, fish oil, corn oil, etc., and then dispersed in mineral oil to produce an extreme-pressure lubricant. In practice, a simple extreme-pressure oil might contain about 10 per cent of fatty oil and 1 per cent of sulfur, which is the important ingredient when a break in the oil film occurs, but the presence of the fatty oil automatically raises the normal load-carrying ability of the oil film.

For heavy-duty industrial gear and automotive service, lead is commonly employed in many E.P. formulas. Lead soap compounds may be manufactured by combining soft lead oxide with oleic acid, the latter being an oily glyceride type of liquid secured from animal fats. This type of extreme-pressure lubricant is generally a combination product containing sulfur, chlorine, or other reactive material in addition to 1, 2, or 3 per cent of lead. The complete compound is then added to the mineral oil. In practice, lead soaps prevent corrosion, particularly if moisture is present, and they also tend to produce antiweld oxides consisting of lead sulfide or lead chloride when high temperatures take place, owing to metal contact between gear teeth. This reaction is, therefore, accomplished to some extent at the expense of the lead, rather than at the expense of the metal on the gear teeth, because lead has a much lower melting point than steel.

Chlorine compounds and chlorinated oils are believed to be more active in the prevention of wear at lower temperatures than sulfur and sulfur compounds. Hence both elements are sometimes used in E.P. oils. In this connection the action of the well-known cleaning compound, carbon tetrachloride, is almost phenomenal when employed as an extreme-pressure medium in gear lubricants. However, the various claims made for different types of extreme-pressure lubricants are based on wear-preventing properties under operating conditions that are extreme, and in this discussion it would be impracticable to express any definite opinion regarding the merits or demerits of the many formulas employed. As a general rule, the average content of a reactive element in an extreme-pressure oil is 1 to 2 per cent, and for automotive duty there is often an additional 1 per cent of lead. Furthermore, many lubricants contain more than one element, as, for example, a combination of sulfur and chlorine, etc.

When this problem was originally tackled by investigators, the average content of extreme-pressure materials in E.P. oils ran high. For example, the following formula was representative up to about 1938:

	Per Cent
Fatty oil	25
Sulfur	5
Lead	5
Mineral oil added to above compound	65

However, the large percentage of reactive material in these oils had a tendency to produce too much plating material on the gear teeth, particularly on hypoid gears, where this type of oil is mostly used. This excessive formation of iron sulfide, iron chloride, etc. (depending upon the element used) was found to be actually abrasive, so that the tendency now is to use it very sparingly. In fact, 1 per cent or even less of an element such as chlorine, sulfur, and phosphorus has been found sufficient for average requirements. This lowering of the E.P. compound also provides a more stable oil in service, without sacrificing any of the chief advantages. Some of the active element is of course used up in service, but the operating conditions have to be exceptionally severe to use up 1 per cent. Before this occurs, the oil will generally be found unfit for further service as a result of oxidation and consequent sludging, due in part to the occurrence of high temperatures on the teeth.

Obviously, there is no advantage in using extreme-pressure lubricants of the chemically reactive type unless the dynamic pressures are sufficient to disrupt the oil films and cause intense local heating action on the gear teeth. However, this action sometimes occurs in heavily loaded spur, herringbone, and helical gear reductions, as, for example, in steel-mill applications, where extreme-pressure oils are occasionally employed in splash and circulating oiling systems applied to reduction gears.

Extreme-pressure lubricants are not as stable and do not last as long as straight mineral oils because the chemical reactions which occur in service tend to shorten the useful life of the oil charge. The presence of moisture will affect some extreme-pressure oils in various ways, depending upon the ingredients. However, considerable progress has been made in the art of manufacturing extreme-pressure lubricants, and under normal conditions they are noncorrosive in service and little affected by the presence of moisture.

Extreme-pressure materials are available which do not adversely affect the demulsibility of the oils to which they are added, and such products are worthy of investigation in the general consideration of circulating oils for reduction gears, particularly installations designed for severe duty. The results of adding one of them to a straight mineral oil having good demulsibility and a Saybolt universal viscosity of 154 seconds at 210° F (S.A.E. 140) are indicated in the following table giving load ratings on different test machines. While this particular test was run on a heavy oil, similar results are obtainable with lighter oils.

	Load Values (in Pounds)	
Test Machine	*Mineral Oil*	*Compounded Oil*
Almen machine	8	18
Timken machine		
Rubbing speed, 400 fpm	22	27
S.A.E. machine		
Roll ratio, 14.6:1		
Loading rate, 83.5 pps		
Speed, 890 rpm	63	76
	Wear Tests	
	Mineral Oil	*Compounded Oil*
Timken machine		
Rubbing speed, 400 fpm		
Lever load, 22 lb		
Loss in grams	0.0015	0.0012

The additive used in making the above test did not adversely affect demulsibility, and it will be noted that wear on the Timken lubricant tester, at a constant load, showed a decrease in favor of the compounded oil. It will also be noted that the degree of improvement in load-carrying capacity depends largely upon the test machine employed and the purpose for which it was developed. The Almen machine showed an increase in load-carrying capacity of 125 per cent, while the Timken and S.A.E. machines showed increases of only 23 per cent and 20 per cent, respectively. This is not unexpected, because film strength is not a sole function of the lubricant but a joint property of the lubricant and the metals composing the frictional surfaces, influenced by speed and the condition of the opposing metal surfaces. These tests on different machines clearly demonstrate why it is impossible to make a general statement giving the load-carrying capacity of any lubricant in terms of a specific number of pounds per square inch pressure. The results on different machines when converted to pounds per square inch pressure vary to a considerable extent, and on any one machine the load-carrying capacity of the same lubricant will be different with steel against steel, steel against bronze, and so on.

Analysis of Gear Teeth Wear

The seven general classes of wear on gear teeth are outlined in the following paragraphs. The first four are not generally attributed to faulty or insufficient lubrication, but, in the case of pitting, improvement may sometimes be secured by the use of a heavier oil or a compounded oil.

1. *Pitting* appears to be the result of a metal fatigue caused by repeated high-compressive stresses occurring on curved surfaces under rolling loads of high magnitude. This condition occurs along or close to the pitch line where rolling contact exists, and, when the stresses set up exceed the compressive endurance of the metal, particles or flakes fall out of the surface, leaving pits.
2. *Abrasion* is caused by the presence of foreign matter such as grit or metallic particles between the opposing surfaces under rolling or sliding contact. It results initially in scratches or grooves running in the direction of sliding between the opposing surfaces, and if the abrasive material is not removed measurable wear eventually occurs.
3. *Scoring,* or *cutting,* takes place when, because of other types of wear, rough surface finish, misalignment of parts, or other imperfections, sharp corners are present which cut through the film of lubricant and score the mating surfaces. A scored surface may sometimes resemble an abraded surface, and, generally, when scoring is present, some abrasion is also present because the particles of metal scored out will act as abrasives. In general, cuts and scratches resulting from scoring will have a more regular pattern than those caused by abrasive foreign material. Most scoring is the result of poor workmanship, but it does not often occur if the mating surfaces are accurately designed and machined.
4. *Spalling* is a type of surface failure similar in some respects to destructive pitting. It results in the shearing out of flakes of metal of appreciable size, but it does not appear to be a condition that is caused by fatigue. It generally occurs on the softer and more ductile metals and takes place when the shear stresses set up by movement of the wave ahead of the contact area exceeds the shear strength of the material. This form of pitting often occurs with new gear sets operating under heavy loads and generally ceases when the mating surfaces

have been cold-worked during the running-in period so that plastic deformation is reduced.

5. *Galling,* or *scuffing,* results from a momentary failure of the oil film, sometimes causing high local temperatures and also a plastic flow of the skin surface of the material. This galling on more ductile material results in a ridge at the pitch line of the driven gear and a hollow at the pitch line of the driving gear, because sliding is toward the pitch line on the driven gear and away from the pitch line on the driving gear. In severe cases this action along the pitch line is accompanied by wiping or wear of metal along the faces and flanks of the gear teeth. Galling often takes place when the loads are heavy and the oil film is not strong enough to support the load, with the result that momentary metallic contact is of frequent occurrence.

6. *Seizing* in many respects is an extreme case of galling. In seizing, local temperatures are so high during the momentary failure of the oil film that particles of metal actually weld onto the contacting surfaces. The particles so welded then act to score succeeding tooth surfaces, thus causing rapid failure of the gears.

7. *Rusting.* Reduction gear teeth will sometimes show excessive signs of wear without any apparent cause. Sometimes this condition results from the formation of moisture in the housing, which produces rusting. The water simply condenses from the atmosphere, and the sweating effect is often capable of forming enough water to accomplish considerable damage over a period of time.

Gear housings should be adequately vented to allow a breathing effect. Highly refined oils permit rusting unless inhibitors are employed. Rusting was a serious difficulty with turbine-grade oils before antirust agents were utilized.

Mineral oils which contain a small percentage of animal or vegetable oil have low surface tensions and are more or less hygroscopic, which means they will absorb moisture and produce an emulsion. As a result of these features, compounded oils provide good protection against rusting, but, owing to their emulsifying tendencies, these oils are not always satisfactory for gear lubrication, particularly if the gears are lubricated by a circulating oiling system. Splash-oiled gears are not generally equipped with adequate means to extract water from the housings, whereas circulating oiling systems are generally equipped with a centrifuge, settling tank, or similar device which eliminates water. Hence splash-oiled gears are more susceptible to rusting.

Suitable Gear Lubricants

Herringbone and helical gears have lower unit surface pressures than spur gears and as a rule require lighter oils. Fine-pitch herringbone gears with a multitude of contact areas require lighter oils than coarse-pitch gears of the same type. This is strictly in accordance with the best practice. For example, high-speed turbine gears are designed with fine pitches and operate best with light oils.

Slow-speed, heavy-duty drives require heavy oils, and, since most of them are splash oiled, the normal recommendation is a correspondingly heavier oil than for the previously mentioned applications.

When gears are of the open type, the best lubricants are those which require heating before they can be brushed onto the teeth. When this type of heavy residual oil cools on wheels and pinions it regains its former body and provides a strong, tacky oil film. Greases are not generally as suitable, and, if heated, the soap content tends to separate from the oil upon cooling.

Gear manufacturers generally supply a plate or a tag which indicates the viscosity, A.G.M.A. number, or the S.A.E. number of the oil best adapted to a particular unit. However, the recommendations below, which are based on a wide survey of actual operating conditions, may be used as a guide.

Hypoid Gears

Compounded steam-cylinder oils are sometimes suitable for use in hypoid gears designed for industrial service when the pinion shaft is offset only a few inches on a large gear wheel. However, the extreme-pressure qualities imparted to mineral oils by tallow or lard oil are not always sufficient to meet the operating conditions.

Lightly loaded hypoid gears may be operated on turbine-grade oils. It is only when gears are subject to extreme pressure or shock loads that welding can take place and an E.P. lubricant is required.

Lubrication Guide for Reduction Gears

INDUSTRIAL AND MARINE TURBINE REDUCTION GEARS

Type of Gear	*Method of Application*	*Viscosity Saybolt Seconds at 100° F*	*A.G.M.A.*
Single reduction	Circulating oiling system	300 to 400	2
Double reduction	Circulating oiling system	400 to 600	3

SPUR, HERRINGBONE, HELICAL, AND BEVEL GEARS

Loading on Gear Teeth	*Method of Application*	*Viscosity Saybolt Seconds at 100° F*	*A.G.M.A.*
Light	Splash	300–600	2 or 3
Moderate (high speed)	Circulation	300–600	2 or 3
Moderate	Circulation	400–800	3
Moderate	Splash	400–800	3
		Saybolt Seconds at 210° F	
Heavy	Circulation	80–150	5, 6, or 7
Heavy	Splash	125–200	7 or 8

Note 1. The higher the pinion speed, the lighter the oil. For multispeed reductions involving more than two wheels, a compromise in viscosity is necessary to meet the requirements of the driving pinion as well as the final reduction. For splash-oiled gears operating on heavy loads, a steam-cylinder oil containing 5 per cent tallow or lard oil will increase the load-carrying ability of the oil films. For extreme-pressure conditions 1 per cent of extreme-pressure element in the oil is recommended. This means 1 per cent of chlorine, sulfur, phosphorus, or other element.

Note 2. The addition of an antirust compound may be specified in straight mineral oil.

WORM GEARS

Light-Duty Examples	*Worm Speed: Operating Data*	*Method of Application*	*Viscosity Saybolt Seconds*	*A.G.M.A.*
Automatic machines, liquid paddle drives,	Up to 1800 rpm	Splash	80 to 125 at 210° F	5 or 6
		. .	.	. . .
etc.	Open type	Slush pan	200 to 500 at 210° F	. . .
Heavy-Duty Examples				
Elevator worm gears, rubber	Oil temp. to 160° F	Circulation	700 to 1000 at 100° F	4
mill drives, car pullers,	Up to 1800 rpm	. . .	. . .	7 Compounded
winches, etc.		Splash	125 to 160 at 210° F	. . .

Note. For the majority of worm gears lubricated by the splash-oiling method the mineral oil should contain about 5 per cent of tallow or lard oil. When the unit is lubricated by a circulating oiling system a straight mineral oil is generally preferable.

The more accurate the gears, the lighter in viscosity the oil should be. Many precision gear sets are operating on 100 S.U.S. at 100° F oil.

Oil Changes for Reduction Gears

When a splash-oiled reduction gear is new, the oil charge should be changed or carefully filtered within 2 weeks, for the reason that finely crushed particles of metal have been found to possess an active catalytic effect which rapidly oxidizes mineral oils. These impurities result from wear during the run-in period. In addition, they are of course abrasive. The first month of operation is easily the most critical in the life of a reduction gear. Incidentally, a pocket magnet is an infallible instrument for detecting metallic particles in samples taken from gear housings.

After this run-in period, the oil should be maintained in a usable condition. Periodic oil samples should be taken to determine the condition of the oil. The sample should be analyzed for dirt, metal, and water content, together with acid number, interfacial tension, and viscosity. Foreign matter can be removed by filtering and the oil reused if the other properties have not changed significantly.

In circulating oiling systems the charge may often be used for several years without change, particularly when adequate filtering equipment is employed to remove impurities. The filter may be a centrifuge, toweling, or fuller's earth. However, with a compounded oil, fuller's earth is not generally recommended for the reason that, while clay is a highly effective filtering medium, it tends to clog and remove the materials employed in compounded oils.

When a circulating oil system requires cleaning, the oil reservoir must be cleaned. Circulating systems should be cleaned once a year: the oil reservoir with kerosene and dry rags that are free from lint, and the piping with pull-through rags at the end of a wire. If an oil cooler is employed, deposits can sometimes be blown out with compressed air, but if they have formed a tenacious coating on the tubes, a cleaning compound may be required to dislodge them.

The table shows an analysis of a heavy circulating oil supplying large heavy-duty gears in a steel mill.

Type of oil	Straight mineral
Length of service	2 years, 3 months
Gravity A.P.I.	30
Flash, °F	540
Viscosity, Saybolt seconds at 210° F	152
Per cent ash	0.23 (iron oxide)
Moisture	Trace
Neutralization number (Mg KOH)	0.14
Per cent insoluble in naphtha	0.32
Per cent insoluble in benzol	0.30

This analysis showed that after a period of 2 years and 3 months the neutralization number had risen from 0.05 to 0.14, which was considered normal. The per cent ash was 0.23, and on further analysis this residue was found to be iron oxide. The indications were that, since a trace of moisture was present, the rust was being caused by the water. It was therefore recommended that the oil be filtered or centrifuged more frequently to remove the iron oxide and water. Otherwise, the charge was in good condition and suitable for continued service. The viscosity had not changed.

The oxidized oil present was the difference between the per cent insoluble in naphtha and the per cent insoluble in benzol, or 0.2 per cent, which was considered negligible. The per cent insoluble in benzol contained some iron oxide, the percentage of which was verified by the ash test. Had the neutralization number been 0.80 to 1.00 the sludge content would probably have been higher, the viscosity would also have been higher, possibly 160 instead of 152, and a recommendation would have been made to change the oil.

Gear-Housing Vapors

An important factor in the operation of reduction gears is that of proper venting. Oil vapors are generated on the gear teeth, and these vapors are capable of exerting a destructive influence on the oil charge

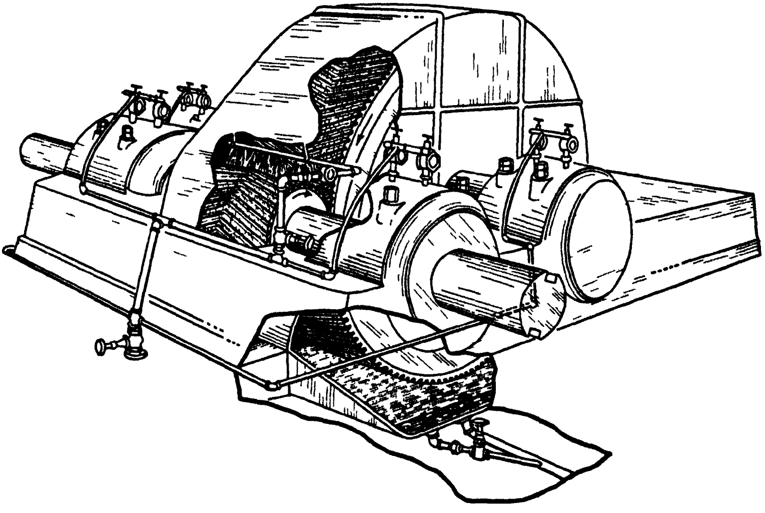

FIG. 9. Reduction gear drive showing method of lubricating gear teeth and bearings by means of a circulating oiling system.

if no provision is made for their escape. Gear housings require "breathing" facilities, particularly if rubbing conditions are severe.

Use of Jets

When gears are lubricated by a circulating oiling system wherein jets are employed to spray oil on the meshing teeth, the oil should be allowed to flow at a reasonable velocity into the contact areas. If the oil is sprayed into the contact areas under high pressure, the force of the oil striking the gear teeth interferes with the automatic oil-wedge action that builds up ahead of the contact areas. This consideration is very important when operating circulating oiling systems with jets directed at the meshing teeth. In very high-speed reduction gears, above 15,000 sfm, the oil is fed into the off side of the gear teeth; otherwise, the hydraulic pressure built up in the meshing teeth would be destructive.

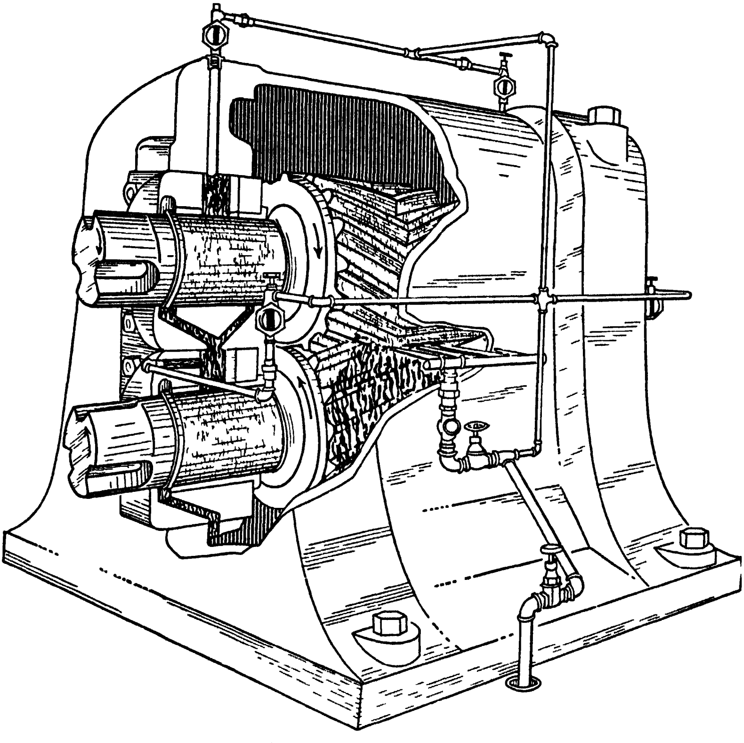

FIG. 10. Pinion stand for rolling mill drive in steel mill, showing method of lubricating gear teeth and bearings by means of a circulating oiling system.

The continuous flow of cool oil is the important factor. Excessive jet pressures and waterfall effects not only tend to destroy the oil-wedge action but actually starve the gear teeth. Figures 9 and 10 illustrate the principles of continuous lubrication by means of a circulating oiling system.

Reference

"Qualitative Analysis of Wear," by Earl Buckingham, *Am. Soc. Mech. Engrs.*, Prog. Rept. 15, Research Committee on Strength of Gear Teeth.

28

Internal-Combustion Engines

Definition of Cycles

In the following chapters on gasoline and Diesel engine lubrication, reference will be made to operating cycles, wherein engines are classified as two-cycle or four-cycle. The following sketches illustrate the definitions.

Two-Stroke Cycle

Figures 1 and 2 illustrate the two-stroke cycle applied to a Diesel engine. When applied to a gasoline engine the events are similar.

The first stroke of the two-cycle engine starts with admission of fresh air, which blows out the remainder of the exhaust gas from the previous power stroke and fills the cylinder with a new charge of air. As the piston moves up it closes first the intake port and then the exhaust port, and from that point on it compresses the air until near top dead-center position, where the fuel is injected and ignites on meeting the hot compressed air. Upon reaching top dead center the power stroke begins. The ignition of the fuel raises the pressure and, as the piston moves down, the gases expand, doing work on the piston, which is converted to rotary motion by the crank mechanism. As the piston nears the bottom of its stroke the exhaust port is uncovered, which releases the pressure in the cylinder and allows most of the exhaust gas to escape. Shortly afterward, the intake port opens and the inrush of fresh air helps to remove the remainder of the exhaust gas, or to "scavenge" the cylinder, thus preparing it for the next working cycle.

The type of engine illustrated is known as a crankcase scavenging engine, but generally a separate pump is employed to carry out the scavenging operation for the reason that oil spray from the bearings tends to be drawn into the air stream with the former design. (See Fig. 3.)

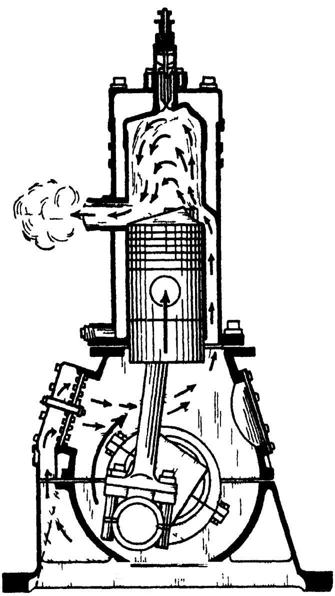

Fig. 1 Compression stroke Two-stroke cycle

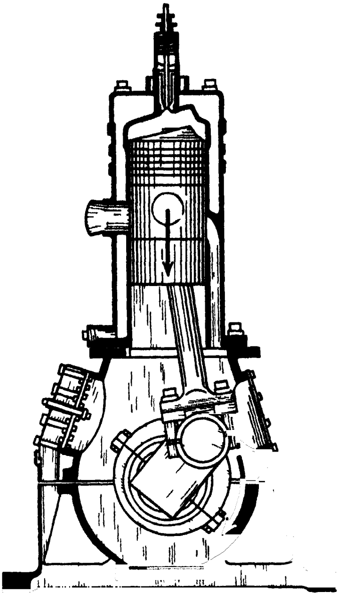

Fig. 2 Power stroke. Two-stroke cycle.

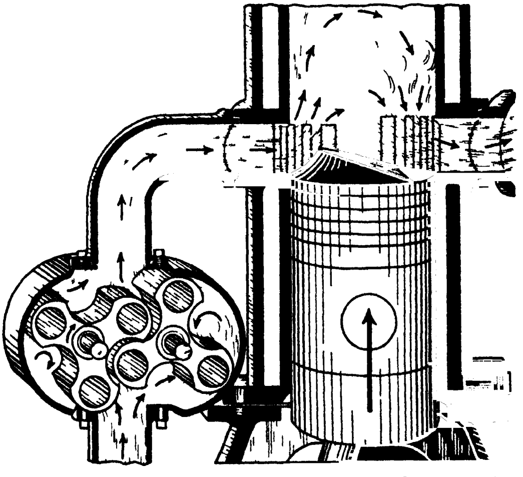

Fig. 3. Rotary displacement blower applied to a Diesel engine for scavenging the cylinder when operating on the two-stroke cycle.

In the Diesel engine field, attention has been concentrated on the two-cycle engine because its operating principle has the advantage that, for a given cylinder size and speed, the engine can develop more power than a four-cycle engine of similar size, since there are twice as many power strokes for a given number of crankshaft revolutions; therefore, the two-cycle engine takes up less room and is lighter than a four-cycle design of the same horsepower and speed. However, the two-cycle engine is not as economical in fuel consumption.

One of the fundamental features of the two-cycle principle is that in order to aid in blowing out the exhaust gases from the cylinder there must be a large supply of air. This air is generally supplied by a pump. In a Diesel engine this is not a drawback, since the cylinder must be charged with air, but in a gasoline or carburetor-type engine the charge consists of an air-fuel mixture, and the same operation would blow out about 25 per cent of this air-fuel mixture. The gasoline two-cycle engine draws air and gasoline into the crankcase on the upstroke of the piston. On the downward stroke of the piston, compression occurs in the crankcase, forcing the gas-air mixture into the cylinder when the intake port has been uncovered. Near the top of the stroke the spark fires the mixture. The vast majority of gasoline engines are four-cycle, and most Diesel engines are two-cycle.

Four-Stroke Cycle

The four-cycle engine employs the same sequence of operations, but the mechanical control is different, as shown in Figs. 4 to 7, which illustrate the events occurring in a Diesel engine.

The first stroke starts with the piston at top dead center, where the air-intake valve opens. The piston moves down, sucking in a charge of air by reducing the pressure inside the cylinder. At the bottom, the intake valve closes and the compression stroke begins with both valves closed. Shortly before reaching top center, fuel is injected into the hot compressed air and thereby ignited, thus starting the third or power stroke. At the completion of this stroke the exhaust valve opens, and the piston, rising on the fourth stroke, discharges the exhaust gas through the open valve. As the piston reaches the top, the exhaust valve closes and the air intake valve opens, thus preparing the engine for another working cycle.

Effect of Supercharging on Cylinder Lubrication

Supercharging is employed to increase the volume of air entering the cylinders of internal-combustion engines. The intake pressures above

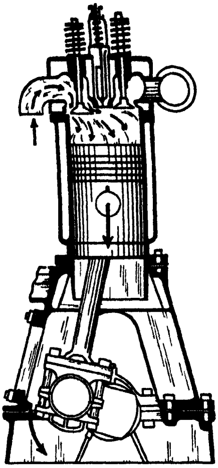

Fig. 4. Air intake.

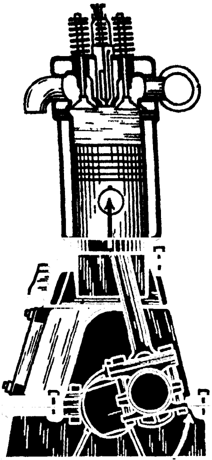

Fig 5. Compression.

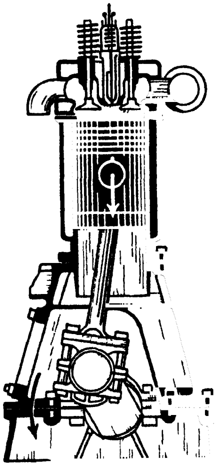

Fig. 6. Power.

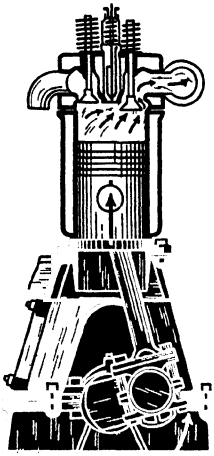

Fig. 7. Exhaust.

Four-stroke cycle.

the piston are increased to permit more fuel to be burned with a corresponding increase in power. This does not require the use of heavier oils. This fact is mentioned because the question sometimes arises in considering an oil of suitable viscosity for a particular engine equipped with a supercharger. This device, which is simply a fan, is generally installed to compensate for the loss of air pressure at high altitude, but it is also used on internal-combustion engines operating at sea level in order to boost the supply of air and thereby to increase the power.

Cylinder Wall Surfacing

After cylinder walls have been machined and honed the apparently smooth surface retains distorted metal particles of minute size. In order to reduce this initial roughness, cylinder walls may be surfaced by various methods to avoid initial scoring.

Chemical surfacing is carried out in a bath containing caustic sulfur and phosphate compounds, which are very effective in removing the free ferrite, pearlite, etc., from cast iron surfaces.

Plating is another method employed to surface new cylinder walls. This method provides a hard coating or skin of microscopic thickness which cuts down the effect of initial abrasion. Chromium is the most widely used material for plating purposes.

Break-In Oils

For the purpose of breaking in new engines, and particularly rebored cylinders, several types of break-in oils may be used to advantage. The compounds employed are soluble in mineral oil and are generally of the extreme-pressure or chemically reactive type. The basic materials employed are compounds of sulfur, chlorine, phosphorus, and similar reactive elements. The purpose is to prevent welding of minute high spots between piston rings and cylinder walls during the break-in period. When metal-to-metal contact occurs between high spots or loose particles, the intense local heat of friction causes the compound to become chemically reactive with the metal surfaces, forming smooth metallic oxides which prevent the seizing or welding action which would otherwise occur.

At the end of the break-in period, the crankcase should be thoroughly flushed out with a light oil before the charge is renewed with a standard grade of lubricating oil. Laboratory tests have shown that considerable metal is often present in samples of break-in oils taken from crankcases.

The use of break-in oils which prevent scoring causes many engines to be broken in too rapidly. A too rapid break-in may cause in 500 miles an accumulation of metal in the oil which would normally accumulate in 3000 miles. Therefore, oil changes should be frequent for rapid break-in.

Cylinder Wall Temperatures

On the power stroke of a piston the maximum temperature of combustion is about 3600° F, and as the gases expand the temperature drops to about 2000° F just before the exhaust valve opens. At first glance these temperatures would seem prohibitive for the heaviest lubricating oils made. However, these temperatures take place only during a relatively brief interval of the complete operating cycle.

If the engine is designed on the almost universal four-stroke principle, the second stroke of the piston expels the rapidly cooling exhaust gases, the third draws in a charge of cool air and gasoline, and the fourth compresses and fires the mixture for the power stroke. Hence there is a marked cooling effect from these events. Furthermore, all cylinders are equipped with liquid cooling jackets or radiating fins exposed to the rushing air, and the net result is an average cylinder wall temperature of about 350° F for liquid-cooled engines and about 400° F to a maximum of 450° F for air-cooled engines.

In all cylinder designs the oil film clings to a relatively cool surface, and the supply is replenished on each stroke of the piston. Hence the worst that happens is a slight scorching effect on a small percentage of the molecules comprising the outer layer of the oil film.

The thickness of the oil film on a cylinder wall is somewhat controversial, but $^{1}/_{1000}$ of an inch may be accepted as close to average. When all these factors are taken into consideration it is not difficult to understand why piston rings and cylinder walls remain apart during operation. The proof is well demonstrated by the fact that any automobile engine receiving reasonable care is capable of traveling 100,000 miles before requiring major repairs such as new piston rings, cylinder reboring, or possibly both.

Diesel Engines

Diesel engines have a higher thermal efficiency than gasoline engines and operate with higher combustion temperatures. The present theoretical maximum efficiency obtainable with a gasoline engine is 33⅓% of the total heat content in the fuel, but in a Diesel engine the maximum theoretical efficiency is 45 per cent.

In a Diesel engine operating temperatures are higher at the end of the air compression stroke, owing to greater compression pressures. These pressures average 450 to 550 psi in comparison with 90 to 120 psi in spark-ignition engines. In general, there is an increase in temperature of about 2° F for each pound in compression pressure. Thus 500 pounds compression in a Diesel engine would generate a temperature of about 1000° F if heat losses are left out of consideration.

The peak temperatures of combustion may reach, and even go above, 3600° F, and the temperature of the expanded and burned gases may average around 1500° F just before the opening of the exhaust valves.

Owing to the method of charging fuel to the cylinders, the spark-ignition-type engine is cooled during the suction stroke by vaporization of the fuel, but this effect is absent in Diesels.

In spite of these higher temperatures the cylinder wall temperatures are seldom higher than 350° F, owing to adequate water circulation and jacketing.

Piston Temperatures

Gasoline Engines

Piston head temperatures are difficult to measure, but for average passenger-car operation the hottest part in the cast-iron type is about 600° F and about 525° F for aluminum. When the piston head is cooled by means of an oil jet these temperatures may be reduced by 100° or 150° F, depending upon the size and design of the piston, volume and temperature of the oil supply, etc. These estimates are very rough but give some idea of engine lubrication as influenced by the temperatures prevailing in this section of the engine. (See Figs. 8 and 9.)

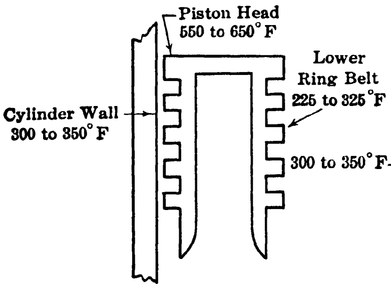

Fig. 8. Cast-iron piston showing approximate operating temperatures.

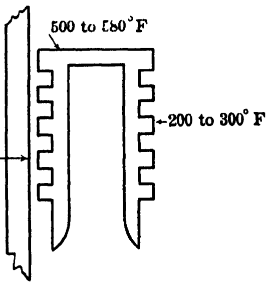

Fig. 9. Aluminum piston showing approximate operating temperatures.

Aluminum pistons dissipate heat faster than cast-iron pistons and therefore operate at a lower temperature. In addition, varnish or any hard gummy type of deposit has less tendency to stick to aluminum.

The design of piston heads and rings is a very important factor in the operation and lubrication of internal-combustion engines. In fact, a change in the design of the pistons will sometimes alter lubricating results to a marked extent. For example, if the heads are designed too thin, for the purpose of cutting down weight, there is a point where the amount of metal becomes insufficient to transfer the surplus heat from the center of the piston to the rings, and thence to the cylinder walls. This excessive heat produces carbon on the underside of the piston, which results in lubricating difficulties; and breakdown of the oil charge is correspondingly rapid as the charge strikes overly hot pistons. Excessive carbon deposits on the underside of the pistons break away and fall into the crankcase. The carbon deposits in the oil pan are often called "coffee grounds." A change in piston design is the best remedy for this condition.

Diesel Engines

In high-speed Diesels equipped with aluminum-alloy pistons the average maximum temperature at the top of the piston is about 650° F. The temperature of the top compression ring generally ranges from 475 to 500° F, and in the four-ring type of piston the temperature of the bottom compression ring will be about 350° F. Generally speaking, temperatures at corresponding points in spark-ignition engines are about 50 to 100° F lower. Diesels equipped with cast-iron pistons operate with higher piston temperatures, the average range being possibly 700 to 750° F at the crown of the piston.

Piston Cooling

In large engines it is possible to control the operating temperatures of pistons by methods which are not considered practical for small engines on account of the extra equipment required. The trend in large engine design is toward double-acting two-cycle engines. (See Fig. 10.) In these engines there is one power stroke for each stroke of the piston, and high piston temperatures are developed.

Piston cooling has a marked effect in retarding the formation of piston ring deposits. To cool the pistons in large engines, it is common practice to circulate a liquid through them. Water is sometimes used because it pumps easily and extracts heat better than other liquids. However, water has the disadvantage that it carries oxygen, which materially assists in causing corrosion, and, if any leaks develop, the lubricating oil becomes contaminated with water. For these reasons, many engines use oil as a preferable circulating medium, either the

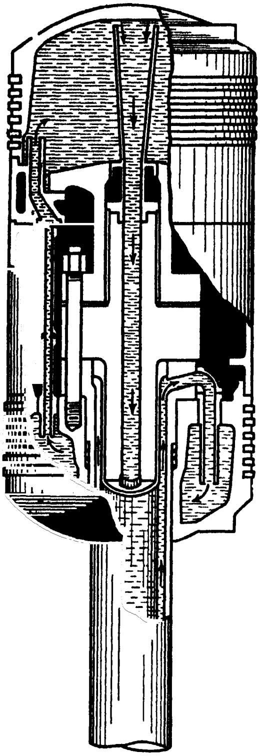

FIG. 10. Double-acting piston showing oil-cooling arrangement. Telescoping pipes are designed to carry the oil to and from the piston. These pipes are not shown in the diagram.

crankcase lubricating oil or a lighter oil that will circulate more rapidly. This practice eliminates the possibility of corrosion and prevents damage to the lubricating oil should a leak occur. Even if a light circulating oil is used, the only result of a leak is a thinning of the crankcase oil, which is not injurious to the engine unless allowed to continue for a long period. If the crankcase oil is used for piston cooling, a leak will naturally do no damage to the oil.

In a piston-cooled engine, the oil is pumped through swing-jointed telescoping pipes, which deliver the oil into a drilled passage in the piston rod. From here, the oil travels around passages in the piston head and returns by means of another drilled passage in the piston rod, then through telescoping pipes and swing joints to an oil cooler.

Another method which is sometimes installed on smaller engines of the trunk-piston type is to direct jets of oil at the inside area of the piston. For this purpose the crankcase oil is generally used. Although the over-all working temperature of the oil is raised, the compromise favors the operation of the engine because piston ring deposits are reduced as a result of the lower operating temperature of the piston head.

As with gasoline engines, the design of piston heads and location of rings is a very important factor in the operation and lubrication of Diesel engines. In fact, a change in the design of the pistons will sometimes alter lubricating results to a marked extent.

Temperatures of Crankcase Oil

Gasoline Engines

Owing to the relatively small amount of space available for the oil charge, there is considerable variance in crankcase operating temperatures. For example, when a passenger car is driven steadily at a speed of 60 miles an hour, the crankcase oil may reach a temperature of 250° F. At speeds above 70 miles the temperature may rise much higher. Tractor trucks operating at full load develop crankcase oil temperatures of about 300° F. The main source of this heat comes from shearing the oil in the bearings. (As developed in the section on "Hydrodynamic Theory of Lubrication" in Chapter 15, viscosity is the friction of a lubricant and must be dissipated in the form of heat.)

These crankcase oil heat estimates are very rough, but they give some idea of the actual operating temperatures. The ideal temperature for crankcase oil would be about 160 to 180° F, but this operating condition is seldom achieved for the reason that means are not provided to cool and regulate crankcase oil temperatures. The space required for extra equipment to accomplish this result would in most applications be prohibitive.

The arbitrary temperature of 160 to 180° F is based on a compromise wherein moisture would be automatically driven off as it tends to collect in the crankcase, and at the same time a temperature of 160° F would be low enough to prolong materially the life of the oil. In expensive high-performance engines, such as aircraft and marine engines, oil coolers are provided to ensure required operating temperatures.

Under low-speed engine operation or in very cold climates, oil viscosity can become too high for efficient lubrication. Then oil heaters are of value.

Diesel Engines

Crankcase oil temperatures, particularly in small high-speed Diesels, where space is at a premium, reflect the temperatures prevailing in the cylinder areas and frequently reach 250° F and higher. Preferred crankcase oil temperatures are about 160 to 180° F, which is high enough to drive out any water that may enter the charge as a result of steam condensation occurring in the cylinders, a condition which is common when the cylinder walls are cold upon starting the engine, and particularly in cold climates and outdoor operation.

Various methods are used to maintain crankcase oil temperatures within reasonable limits. Where space is available, the most popular method is to cool the oil by pumping it through an air cooler. Hence, the problem of crankcase oil temperature is generally nonexistent in the larger engines, and the life of the oil charge is lengthened thereby.

For the trunk-piston-type engine, splashing oil from the bearings to the cylinder walls, it should not be inferred that maintenance of crankcase oil temperatures below 160° F would ensure satisfactory Diesel lubrication. In the critical upper-cylinder regions oxidation conditions on the lubricating oil are about 60,000 times greater at 600° F than at 160° F. However, the lowering of crankcase oil temperatures would obviously be advantageous if it were practicable to install the necessary extra equipment in all types of engines.

Filtering Crankcase Oils

Various methods may be used in filtering the crankcase oil in Diesels. For straight mineral oils one method is to heat the oil to about 300° F, which drives off a percentage of any fuel dilution that may be present, and then to filter the oil through clay or fuller's earth, which effectively removes carbon, soot, sludge, and metallic particles. This type of filter has been perfected to a point where it is a self-contained unit, almost automatic in operation.

Over a period of time, continual filtration sometimes lowers the viscosity of the oil because a percentage of the higher-boiling-point fractions of fuel oil are not removed. In the event that noticeable fuel dilution is taking place, the filtered lubricating oil may be raised in viscosity by adding a percentage of new oil that is one S.A.E. grade heavier.

Combination clay and heat purifiers are popular and effective for large installations using oils that do not contain carbon-dispersing compounds. They cannot be used to the same advantage with oils that contain additives because clay has a definite tendency to remove such compounds, but for large engines the advantage gained by the use of this filtering method sometimes outweighs the advantage of additives in the lubricating oil.

Another method of purification is to use a centrifuge. This type of purifier will not remove fuel dilution from the lubricating oil, but it requires very little or no maintenance, such as renewing filtering mediums, etc. Centrifuges do not interfere with compounds in additive-type oils, which is an advantage where this type of oil is used.

For smaller engines equipped with a filter on the force-feed system to the bearings, the unit should be large and roomy, regardless of the type installed. Tests carried out on a variety of different filters have demonstrated that size is often much more important than the type of filtering medium, whether it be fuller's earth, cloth cartridge, cellulose materials such as wood fiber or cotton waste, or edge plates, wire mesh screens, etc. Small filters are not nearly as efficient in removing sludge, soot, carbon, etc., as their counterparts three times larger. The cloth cartridge and composition types do not remove detergent compounds and are best adapted to small engines using this type of oil.

Considerable improvement can be effected in Diesel operation by installing the proper type of filtering equipment. The economies obtained in operating maintenance far outweigh the original cost of installing oil-filtering equipment.

29

Gasoline Engines

Before discussing the lubrication of gasoline engines, the fundamental characteristics of gasoline will be outlined. There are several types of gasoline, and, as will be obvious later, a working knowledge of their composition and behavior is advantageous when dealing with practical problems in lubrication.

The maximum thermal efficiency obtainable with a gasoline engine is one-third of the total heat content in the gasoline, which is approximately 19,000 British thermal units per pound; but with heat dissipation as a result of cylinder cooling, radiation losses, exhaust heat losses, etc., the actual road efficiency is about 10 to 12 per cent for a modern automobile engine operating at full load. Hence every advantage is sought to increase efficiency and thereby cut down engine size. All improvements, whether in fuel or engine design, are eventually calculated to the per cent improvement in thermal efficiency.

Startability

The property which imparts quick starting to gasoline engines is governed by the percentage of liquids of low boiling point in the fuel. These liquids atomize quickly with the air in the carburetor and thus ignite easily when the engine is turned over.

The average boiling range of commercial gasoline is approximately 85° to 400° F; consequently the higher the percentage of liquids of low boiling point in the fuel, the easier the starting. However, this percentage has to be maintained within reasonable limits to prevent the difficulty known as vapor lock.

The tests in the table on page 275 show average distillation ranges for three grades of gasoline and give an idea of their volatility. Notice that the winter grade has a higher content of low-boiling-point hydrocarbons than an average summer grade. This precautionary measure is to improve startability in cold weather. In aviation gasolines the blend may be composed of straight-run gasoline, isoöctane, and the addition of tetraethyl lead. This type of gasoline is more volatile, and the boiling points are controlled to a large extent by the isoöctane content, by isopentane, or by any combination of materials which have a high value in antiknock properties.

APPROXIMATE BOILING RANGES OF GASOLINE

	% Distilled Off between 90° F and 145° F	*% Distilled Off between 145° F and 212° F*	*% Distilled Off between 212° F and 250° F*	*% Distilled Off between 250° F and 400° F*	*Approximate Residue Loss, %*	*Heat Content in Btu per Pound*
Commercial summer	10	37	34	18	Below 1	19,000
Commercial winter	15	45	26	13	Below 1	19,000
Aviation	25	64	11	..	Below 1	19,000

* The initial boiling point of commercial winter-grade gasoline is generally about 85° F, and that of aviation gasoline is about 115° F.

Compression Ratio, Pre-Ignition, and Detonation

The compression ratio of an internal-combustion engine is the largest working volume inside the cylinder divided by the volume left when the piston is at the top of its stroke. (See Figs. 1 and 2.)

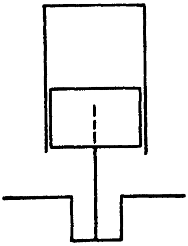

FIG. 1. Largest working volume. Crank at dead center bottom.

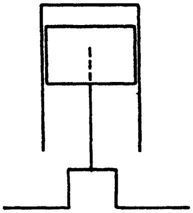

FIG. 2. Smallest working volume. Crank at dead center top.

This ratio has a direct influence on the performance of carburetor-equipped gasoline engines for the reason that straight-run gasolines will not burn evenly in air pressures much above 75 psi, which represents a compression ratio of about 5 to 1. If the compression ratio is increased above 5 to 1 the mixture of hot air and straight-run gasoline within the cylinders burns in a rough and uneven manner, knocking develops, and engine power drops off. This condition is generally referred to as "detonation." The highest practical ratio for gasoline engines equipped with carburetors is about 8 to 1. Ratios higher than this result in compression temperatures which automatically ignite the air and gasoline mixture before the piston has reached the correct firing position on the upward compression stroke.

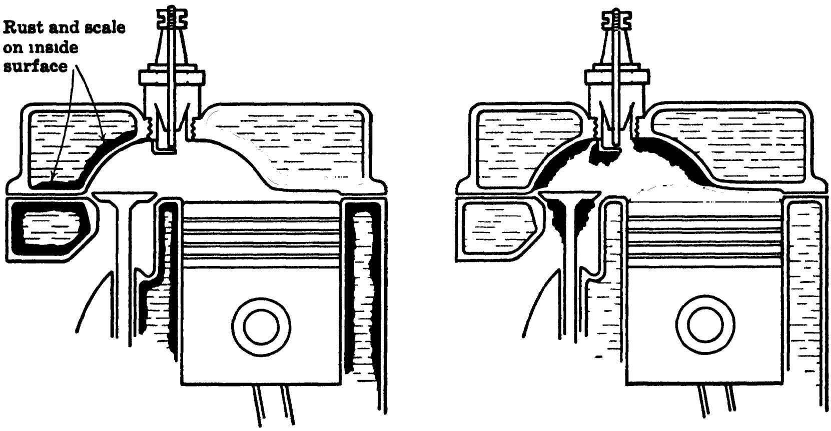

Fig. 3.

To secure uniform burning at pressure ratios above 5 to 1 straight-run gasolines have to be blended with cracked gasoline, isooctane, and similar fuels, or 2 to 3 cubic centimeters per gallon of tetraethyl lead is added to slow up the process of combustion and eliminate rough burning and consequent knock or ping. (See Fig. 5.)

Pre-ignition is generally caused by hot sparkplugs, red-hot carbon deposits, or hot spots due to improper cooling of the cylinder head. Pre-ignition must not be confused with detonation, because pre-ignition can occur with any fuel. If the ignition is turned off, the engine will continue to fire by self-ignition. Pre-ignition may also be distinguished from detonation by the fact that it increases in intensity with an increase in engine speed, whereas detonation generally diminishes as the engine speed increases. See Fig. 3 for sketches which demonstrate pre-ignition and its causes.

Probably the best way to explain the cause of detonation in a gasoline engine is by means of diagrams adapted from actual photographs of the phenomenon. To obtain these photographs, special cylinders are made from a transparent quartz, and a complete laboratory unit is equipped with high-speed cameras and all the necessary timing and recording instruments to photograph the various stages of combustion.

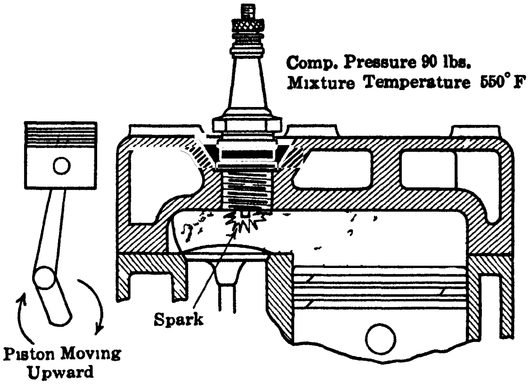

FIG 4 With the spark timed for maximum power, the ignited mixture should burn quickly and evenly, the flame spreading from the sparkplug in a progressive manner, while the piston is moving upward

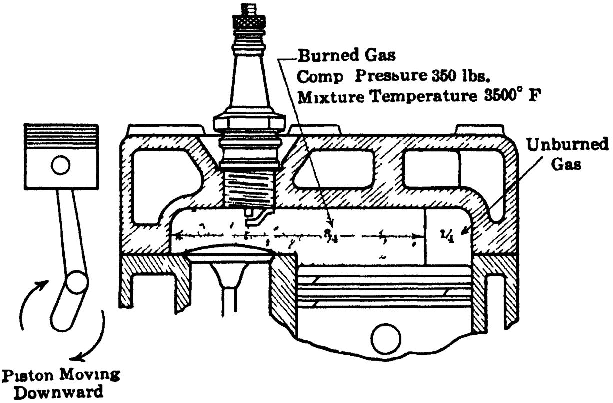

FIG 5 In this diagram, the pressure on the unburned gas at the right raises its temperature When this unburned gas reaches a critical temperature it ignites spontaneously (movement of the crankshaft nil) The detonation wave strikes the surrounding walls and piston head with great violence This action results in knocking or ping

Figure 4 represents perfect combustion, wherein the gasoline and air mixture is compressed and fired when the piston is on its way upward and has about 24° to travel before reaching the top-center position. While the piston is still moving upward the gasoline and air mixture is ignited by the sparkplug and burns progressively until the piston reaches top center, at which point burning ceases, maximum gas pressure is reached, and the piston moves downward on the power stroke with an even pressure exerted by the expanding gases.

Figure 5 is an example of what happens when detonation takes place. When the mixture is fired as before, only part of the charge burns, while the remaining portion is compressed into a corner of the cylinder. When the piston moves downward this unburned portion suddenly ignites, and the detonation wave strikes the surrounding walls and piston head with an explosive violence. This effect results in a metallic-sounding ping within the cylinders, for the reason that during this brief moment of detonation the piston barely moves and is therefore struck a hammer blow which produces little or no power.

Effect of Knock

Engine knock is often accompanied by carbon deposits of soot which tend to combine with the lubricating oil, and the two are baked together. The thumping on top of the pistons may also cause excessive bearing wear. It can wreck large aircraft engines by a combination of thumping and overheating of the pistons and valves, etc. Contrary to general belief, the octane rating of gasoline is more important during warm weather than during cold weather. During the cold months of winter, passenger cars will operate without knocking on lower-octane fuels because the air is colder in the suction line, and the engine is more effectively cooled; these factors lower the final compression temperatures.

The "octane number" of gasoline is a measure of the fuel's tendency to knock. This test was described in detail in Chapter 11, "Functional Tests."

Aviation Gasoline

The most important requirements for aviation fuels are high antiknock value, high average volatility, low freezing point, and greatest possible heat value per unit weight of fuel.

The antiknock value, or octane number, is of much greater importance in aviation engines than in passenger-car engines because aircraft engines develop much more power for the same weight. Furthermore, passenger cars seldom run at more than 20 to 40 per cent of their full power output, while aircraft engines are generally called upon to work continuously at 60% or even more of their maximum power output, and, during takeoff and initial climb, full throttle is used for about 1 to 2 minutes. Working conditions in aircraft engines are, therefore, more liable to give continuous detonation. Although occasional detonation, such as occurs in automobile engines, has no harmful mechanical effect on the engine, continuous knocking in the larger cylinders of aircraft engines causes the power to drop off and also produces severe overheating, followed by burning and seizure of the pistons. Unfortunately, the onset of detonation is not easily detected in aircraft engines, owing to the intensity of other running noises, which are louder than those of automobile engines. It is, therefore, of the greatest importance to use, in aircraft, a fuel of sufficiently high octane number to prevent detonation. A great deal of work is being done to find the best methods of testing aviation fuels in single-cylinder engines such as the C.F.R. engine. This work is directed towards finding the conditions of test in a single-cylinder engine, such as engine speed, fuel-air mixture, temperature, etc., which give fuel knock ratings in agreement with those found in full-size aircraft engines.

In order to obtain satisfactory distribution of fuel between the cylinders, a more volatile fuel is generally required for aviation than for automobile purposes. Furthermore, the fuel in the carburetors of an aircraft engine may, at high altitudes, fall to a temperature of −50° C (−58° F) or lower. The low temperature is due, in part, to the cooling effect of the evaporating fuel. (The cooling effect is analogous to that experienced when ether or alcohol is poured on the hand and allowed to evaporate.) Hence, all aviation gasolines are fluid down to temperatures well below those encountered at high altitudes, and, as a matter of interest, the average grade of commercial gasoline has a natural pour point which is generally below −70° F. Obviously it is very important that contamination with water be carefully avoided when handling and transporting aviation gasoline.

Diesel Fuel

In a Diesel engine the problems of combustion are different from those encountered in a gasoline engine, and for this reason a knowledge of the principal factors which cause this difference are essential. Combustion has considerable influence on lubrication.

Combustion

First, there is a much shorter period of time available for mixing the fuel with the air because the fuel is "shot" directly into the cylinder under high pressure, whereas in a gasoline engine the fuel is thoroughly mixed with air in a carburetor before entering the cylinder. Second, the fuel employed is heavier and less volatile; hence it is more difficult to mix with air and does not vaporize as quickly. If for any reason the fuel is not completely burned, the products of incomplete combustion may yield gum, lacquer-like materials, and soot. Any or all of these products are capable of accelerating deposits in cylinders, piston rings, and exhaust passages and of contaminating the oil charge.

Incompletely burned fuel leaves a fine soot which tends to increase the formation of deposits in piston ring grooves and to contaminate the crankcase lubricating oil. This type of soot quickly blackens lubricating oil, but it is not in itself particularly harmful. However, it will combine readily with any sludge that may be in the crankcase oil. Since Diesel engines operate with a high-compression pressure, which raises the air temperature and ignites the fuel charge without the aid of sparkplugs or other heat-applying device, any factor which interferes with piston ring operation and compression exerts a strong influence on the performance of the engine. A gasoline engine with badly stuck rings and considerable blowby may still operate, but under the same conditions a Diesel engine might not even start, but if it did start it would run with difficulty and would develop very little power.

Fuel Oil Viscosity

Viscosity has been defined as resistance to flow. Light fuel oils are generally tested for this property in a capillary tube wherein a small bore is charged with light fuel at a stipulated temperature and the time taken by the charge to run out is clocked in seconds. The Saybolt thermoviscosimeter, which is used for measuring the viscosity of light fluids, is more accurate than the Saybolt universal viscosimeter, which is employed for lubricating oils. However, to avoid confusion, the reading is generally converted to the scale of the Saybolt universal viscosimeter.

Heavy fuel oils are generally tested in the Saybolt furol viscosimeter, which has a comparatively large orifice but in other respects has the same construction as that of the Saybolt universal viscosimeter. The temperature usually employed with this instrument is 122° F, although temperatures of 77, 100, and 210° F may be used. The word "furol" is an abbreviation of "fuel and road oils."

Viscosity is the number of seconds taken by a liquid to run out of a container. The size of the orifice is standard for each instrument, the volume of liquid is standard, and the temperature is stipulated.

The lighter the fuel oil the more volatile it becomes, and consequently the more readily it burns. As a matter of interest, there is a difference of only about 6 per cent between the total heat content in a gallon of light fuel oil and that in a gallon of the heaviest fuel oil obtainable. Hence it is generally advisable to use light grades and thereby secure better combustion. There are, of course, many large engines designed for heavy fuel where the savings outweigh the improvement in operation, but this is a matter of economics wherein the prices of different grades of fuel must be considered.

Cetane Number

In order to secure uniform combustion, it is highly desirable that the fuel ignite with a minimum of delay upon meeting the high-temperature compressed air. If there is an appreciable time lag between injection and ignition the combustion chamber tends to fill with unburned vapor while injection is taking place on the up stroke of the piston. This initial tardiness results in "knocking" for the reason that a percentage of vaporized fuel may ignite spontaneously when the piston is moving downward on the power stroke. As a result of this action the top of the piston is subjected to a "hammer blow," which does very little useful work, results in loss of power, and produces rough operation.

The ignition lag in the average Diesel operating on a good grade of No. 2 fuel oil is about 0.0008 second or approximately $\frac{1}{1000}$ of a second. This is not important until the engine runs at speeds above 300 rpm. For example, at 2000 to 3000 rpm the ignition lag is or may be much greater than the time allowed to inject the fuel. One of the major problems in Diesel operation is to make the fuel more volatile and cut down the delay in ignition.

The cetane number and Diesel index tests were discussed in Chapter 11, "Functional Tests."

For large engines using heavy fuels, the question of Diesel index or cetane rating is not important because these engines seldom turn at more than 350 rpm. Large marine engines seldom turn at much above 100 rpm and therefore the problem of ignition delay is not so acute. In a slow-speed engine, good combustion is easily obtained because there is more time to burn the fuel completely.

Gravity of Fuel Oils

From an operating viewpoint, specific gravity is important when calculating the Diesel index number. As a general rule the lower the specific gravity, the more paraffinic the structure of the oil. On the A.P.I. scale the higher the gravity, the more paraffinic the oil. High-specific-gravity oils have most Btu per gallon.

Flash Point of Fuel Oils

The flash point is necessary where fire laws specify a certain minimum. All except the lightest grades have flash points above 150° F, which is the usual temperature specified.

Carbon Residue in Fuel Oils: Conradson, Dish, and 10 Per Cent Residue

The test for carbon residue consists in heating the oil until all the volatile material has been evaporated. With different grades of fuel oil from the same crude, this test gives a rough approximation of the carbon-forming tendencies of the oils, but with fuels from different sources, no reliable comparison can be made. In an engine the fuel actually burns in the presence of excess oxygen, the conditions being entirely different from those in the Conradson carbon residue test, where little or no air is present.

Two other tests are employed for laboratory evaluations of the carbon-depositing tendencies in Diesel fuels: the so-called "dish test" and the "carbon residue of 10 per cent bottoms." In the first of these the fuel is heated and ignited on the surface of a porcelain dish shaped like a large cup. The fuel is allowed to burn in the presence of air until it burns out. In this test, if a fuel leaves a tarry, gummy deposit it is likely to cause combustion chamber and piston deposits, which will finally result in stuck rings. This is not a standard test but is of qualitative value, especially for making direct comparisons of fuels.

The "carbon residue of 10 per cent bottoms" is determined by distilling the fuel down to its last 10 per cent and then running the standard Conradson carbon residue test on this heavy fraction. The effect of this test is to give a value based on the high-boiling-point portion of the fuel only, which seems to give fairly good correlation with engine results.

Ash

Ash-forming materials may be present in fuel oil in two forms: (1) abrasive solids and (2) soluble metallic soaps. Abrasive solids contribute to cylinder, ring, fuel pump, and injector wear and to engine deposits. Soluble metallic soaps have little effect on wear but may contribute to engine deposits. For these reasons a low ash content is very desirable.

Sulfur in Fuel Oils

Two different tests are used for evaluating the sulfur content in a fuel oil. The first, the bomb test, measures the total sulfur content; the second, the copper strip test, gives an indication of the amount of corrosive sulfur present. The total sulfur content may or may not be important, depending upon the operating conditions. It is determined by burning a sample with oxygen in a closed bomb and calculating the total original sulfur from the amount of sulfur dioxide formed by the process of complete combustion.

In Diesel engine cylinders the sulfur compounds burn to sulfur dioxide, which in the presence of water forms a corrosive acid. If the engine is operated intermittently or under low temperatures, so that water collects in the crankcase or moisture is left in the cylinders, corrosion will result with a high-sulfur fuel. This will also be true if the exhaust gases are cooled so that water condenses in the exhaust pipes or silencer.

The presence of corrosive sulfur is indicated by immersing a polished copper strip in a sample and maintaining the bath temperature at 122° F for 3 hours, then noting any discoloration. This test is sometimes important to the operator. If a fuel does not pass this test, it can be expected to cause corrosion of the fuel pump barrel, plungers, and the needle in the spray valve, thus seriously interfering with engine performance and resulting in expensive repairs. The presence of corrosive sulfur is important before combustion, whereas the total sulfur is important after combustion.

Pour Point of Fuel Oils

The pour point of an oil indicates the temperature at which the oil will just flow under the force of gravity and below which it may not be possible to pour the oil from a container. While the structure of the oil, the size and shape of the container, and the pressure exerted on the oil have an influence on the pour point, this test gives an indication of the temperature below which it might not be possible to pump the fuel to the engine. The reading is important for engines operating outdoors during winter months where air temperatures may be very low. Under these conditions it may be necessary to warm the fuel to a temperature 11° above its pour point so that it will pump freely; otherwise a pour point should be stipulated.

The pour points of No. 2 fuels vary from about 10° F for paraffin-base types to −40° F for napthenic-base types. The pour point is generally interrelated with cetane number and volatility. Low pour points are generally obtained at the expense of lowering the cetane rating or increasing the volatility. Pour point should not be specified lower than necessary.

Distillation Range of Fuel Oils

The distillation range of a fuel is the range in temperature between the initial boiling point and the final boiling point. If the range is too broad, trouble in operation may result from the heavy portions of high boiling point; however, this factor is covered better by the tests for residue, especially the "dish test." The A.S.M.E. Tentative Specifications are shown in Table 1.

Fuel Oil Specifications

A Diesel fuel specification is best described by a complete laboratory analysis. The following is a complete specification for a No. 2 straight-run distillate fuel.

Gravity A.P.I.	37
Closed-cup flash point	148° F (Pensky Martin Cup)
Pour point	−5° F
Saybolt viscosity at 100° F	37 sec
Per cent sulfur	0.22
Aniline point	148° F
Cetane number	53
Diesel index	55
Carbon residue (Conradson) on 10% bottoms	0.05
Initial boiling point	360° F
Final boiling point	645° F
Per cent recovered at 440° F	22
Per cent recovered at 450° F	28
Per cent recovered at 500° F	60
Per cent recovered at 550° F	86
Per cent recovered at 600° F	97
Per cent lost	1.5
10% recovered at	419° F
90% recovered at	565° F

Additives in Fuel Oils

Straight-run distillate fuels of No. 2 rating have cetane numbers ranging from 20 to 85. An average grade of No. 2 fuel oil generally has a cetane number of about 45 to 55, and the majority of Diesels will operate satisfactorily on these fuels.

Fuels that have been run through the cracking process are not well adapted to good combustion because the cetane number is lowered, owing to the formation of aromatic-type molecules.

Considerable research work is constantly being carried out on additives that will raise the cetane number of No. 2 fuels. Among the many compounds that will improve the cetane number are the following: amyl nitrate, ethyl disulfide, and chloropicrin. The amount re-

TABLE 1. LIMITING REQUIREMENTS FOR DIESEL FUEL OILS *

Grade of Diesel Fuel Oil	Flash Point, °F	Pour Point, °F	Water and Sediment, Per Cent by Volume	Carbon Residue on 10 Per Cent Residuum, Per Cent	Ash, Per Cent by Weight	Distillation Temperatures, °F		Viscosity at 100° F		Sulfur, Per Cent by Weight	Copper Strip Corrosion	Cetane Number
						90 Per Cent Point	End Point	Seconds Saybolt Universal or Kinematic				
	Min.	Max.	Max.	Max.	Max.	Max.	Max.	Min.	Max.	Max.	Max.	Min.
No. 1-D: A volatile distillate fuel oil for engines in service requiring frequent speed and load changes.	100 or legal	20[1]	Trace	0.15	0.01	. . .	625	1.4[2]	. . .	0.50	Negative[3]	40[4]
No. 2-D: A distillate fuel oil of low volatility for engines in industrial and heavy mobile service.	100 or legal	20[1]	0.10	0.35	0.02	675	. . .	. . .	45 sec (5.8)[2]	1.0	Negative[3]	40[4]
No. 4-D: A fuel oil for low- and medium-speed engines.	130 or legal	20[1]	0.50	. . .	0.10	. . .	. . .	45 sec (5.8)[2]	125 sec (26.4)[2]	2.0	. . .	25[4]

Note. Lighter or heavier grades of distillates and heavier grades of residual fuel oils may be procured by mutual agreement between the purchaser and the seller.

* The numerical values contained in Table 1 are similar to those of the corresponding grades of commercially obtainable oil burner fuels except for addition of ash content, sulfur limits, and cetane number. To meet special operating conditions, modification of individual fuel properties may become necessary as outlined below in footnotes [1] and [2].

[1] For cold-weather operation the pour point should be specified 10° F below the temperature at which the engine is to be operated.

[2] Kinematic viscosity in centistokes.

[3] The exposed copper strip shall show no gray or black deposit.

[4] Low atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

quired to raise the cetane number of different No. 2 fuels may vary considerably, but the table shows some test results.

Mid-Continent Cracked	*Cetane Number*
No additive	35
1% amyl nitrate	45
2% amyl nitrate	53
3% amyl nitrate	58

Mid-Continent Straight Distillate	*Cetane Number*
No additive	55
1% amyl nitrate	64
2% amyl nitrate	76
3% amyl nitrate	81

The results of adding various compounds to boost the cetane number of light fuels are not fully established, and the compounds mentioned are merely given as examples. Many of the additives have various detrimental effects when used in actual service.

Filtering of Fuel Oils

Fuel oil should be filtered before reaching the fuel pump to eliminate foreign impurities. Fuel injectors are precisely built to deliver a measured quantity of fuel in as little time as $^{1}/_{5000}$ second, and at high pressure. Any dirt or foreign material causes damage and erratic operation of the engine. The filter employed should be capable of removing very small particle sizes. In this connection the type of filter is not generally as important as the size of the filter. The larger the filter, the more effective its cleaning ability. Clarifiers of the cloth cartridge type make very good filters for fuel oils.

Comparison of Combustion in Diesel and Gasoline Engines

In order to ensure a smooth-running Diesel engine the fuel must possess qualities which would be very undesirable in gasoline engines. The combustion factors are directly opposite in the two types of engines.

Gasoline engines will start to knock or run more roughly if the temperature of the cooling water is raised, if the air temperature is raised, if the compression ratio is increased, or if a more paraffinic type of fuel is used; but any of these changes will result in smoother operation when applied to Diesel engines because they accelerate the combustion of the heavier and less volatile fuel.

Practical considerations often interfere, however, with what may be theoretically desirable. Marine Diesel engines, for example, using salt water for cylinder cooling, have to run with low cooling-water temperatures to prevent the formation of excessive scale in the water jackets. Modern installations employ fresh-water cooling by using a closed system wherein the heat from the fresh circulating water is transferred to sea water by means of a heat exchanger. With this type of system the engine can be run hotter, with improved performance.

Diesel trucks and trains operating in mountainous country frequently experience operating difficulties with crankcase sludge and excessive cylinder deposits. This is due to high-altitude operation, where the lower density of the atmosphere reduces the weight of the air charge per stroke and also lowers the pressure and temperature of compression. These factors tend to cause incomplete combustion, and to overcome this difficulty a pump or supercharger is sometimes installed to boost the air supply. The same is true for aircraft gasoline engines operating at the higher altitudes.

Diesel fuels should contain a minimum of cracked fuel because cracked fuel tends to delay combustion. Straight-run fuels are the most desirable, but economic conditions sometimes make difficult the setting aside of straight-run fuels for Diesel engines. However, if too much cracked fuel is present in the blend the operation of the engine will be affected, and deposits are liable to form in storage tanks and passages. This is brought about by the less stable properties of the cracked fuel and the fact that it may tend to produce a refining action in storage. This action is sometimes responsible for throwing down objectionable materials of a gummy or tarry nature.

Gasoline must perform over a wide range of engine temperature and load. Efficient operation of a Diesel demands a steady load and temperature. Increasing temperature or load causes too rapid burning of the fuel. Lowering the load or temperature causes slow burning of the fuel.

Combustion

All fuels contain hydrogen and carbon and require oxygen for burning. The principal products of combustion are water, carbon dioxide, and carbon monoxide.

In the gasoline and Diesel engine complete combustion does not occur because of the deficiency of air or the heavy ends in the fuel. Most of the noncombusted fuel finds its way out the engine through the exhaust. The part that remains in the engine tends to form deposits which may lodge in the combustion chamber, or blow by the piston to the rings and crankcase.

For every pound of fuel burned, more than a pound of water is formed. Fortunately most of the water goes out the exhaust in the form of steam, and in cold weather some condenses and can be seen dripping from the exhaust pipe. That which blows by the rings condenses in cold crankcases and escapes through the breather in hot engines. Another source of water in the crankcase is condensation caused by cooling.

An appreciable quantity of gasoline finds its way into crankcases through the use of the choke and rich mixtures for idling and acceleration. From 1 to 5 per cent is considered normal, and as much as 20 per cent may be found in intermittently operated engines.

Effect of Lead

Up to 4 milliliters per gallon of tetraethyl lead is used for increasing the octane rating of gasoline. This material is responsible for most of the acids and the corrosive properties of gasoline. The burned tetraethyl lead forms lead compounds, which lodge in the combustion chamber of the engine. Table 2 gives the location and composition of some of these deposits.

TABLE 2. IDENTIFICATION OF LEAD COMPOUNDS FOUND IN AIRCRAFT-ENGINE COMBUSTION CHAMBERS *

Location	*Major Component*	
Exhaust valve dome	$4PbOPbSO_4$	(4 parts lead oxide, 1 part lead sulfate)
Exhaust valve tulip	$PbOPbSO_4$	(Approx. equal parts lead oxide and lead sulfate)
Intake valve dome	$PbOPbBr_2$ $2PbOPbBr_2$	(Lead oxide and lead bromide)
Piston crown	$PbOPbBr_2$ $2PbOPbBr_2$	(Lead oxide and lead bromide)
Combustion chamber walls		
Nodular deposits	$PbOPbSO_4$	(Lead oxide and lead sulfate)
Fused deposits	$2PbOPbBr_2$	(Lead oxide and lead bromide)

Engines operated on grade 100/130 aviation gasoline containing 3.0 to 4.0 milliliters per gallon tetraethyl lead, aviation mix.

* *Lubrication*, October, 1951, The Texas Company.

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Internal-Combustion Engine Lubricating Oil

The internal-combustion engine seems to be lubricated fairly well by three types of oil: regular, premium, and heavy-duty. Generally speaking, regular oils are naphthenic neutral and bright stock blends, with V.I. from 20 to 60, and they do not contain additives. These oils will satisfactorily lubricate low-compression engines with Babbitt bearings, using low-lead-content gasoline. These oils should be used in all two-cycle engines, such as outboards.

Premium oils are blends of a paraffinic neutral and bright stock, with a V.I. from 50 to 100, containing corrosion inhibitors. Such oils should be used where alloy bearings such as lead copper or silver cadmium are found. These oils generally show a somewhat lower oil consumption than the regular type.

The heavy-duty oils were designed to give clean engine operation when using dirty fuels. This is accomplished by adding a detergent to keep the soot and lead compounds in suspension. The heavy-duty oils also contain oxidation and corrosion inhibitors. Figures 1 and 2 show the effect of a dispersing agent added to an oil.

The heavy-duty oils have a tendency to increase exhaust valve burning and cause sparkplug shorting. For this reason this type of oil should not be used in spark-ignition two-cycle engines.

When cylinder walls are comparatively cool, some of the steam formed during the process of combustion condenses, and a percentage works past the piston rings and finds its way into the crankcase. This moisture quickly combines with any oxidized oil and dirt that may be present and forms a characteristic type of sludge. During cold weather these thick emulsions of oxidized oil and water are common and occur more frequently than during warm weather. They are generally termed "winter sludges." By and large the type of oil used has little to do with the sludge. Only the oxidized part is chargeable to the oil. The dirt and the water come from the engine operation.

Sludge conditions can be minimized by frequent oil changes, raising the crankcase temperature, and increasing the crankcase ventilation.

The sludges are usually of a soft greasy nature and cause little trouble, except to freeze, and then they may block oil passages and pumps.

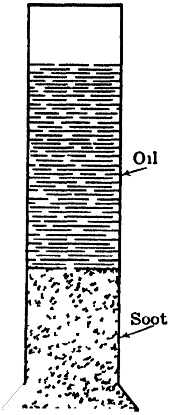

FIG. 1. Before adding a dispersing agent to a sample of mineral oil and soot.

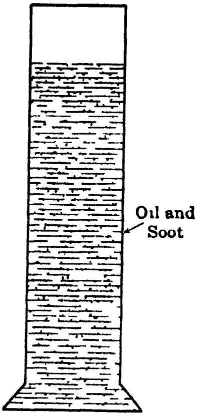

FIG 2. After adding a dispersing agent to the same sample of mineral oil and soot.

Varnish

Among the several types of deposits found on the working parts of internal-combustion engines, much has been written about the deposit referred to as "varnish." The name is descriptive, because these coatings are similar in appearance to commercial protective varnishes. In color they may vary from pale lemon to reddish brown. When they are nearly black they are not customarily referred to as varnish.

Varnish is most likely to be noticed in new engines where it coats the insides of pistons, connecting rods, crankcase interior surfaces, breather pipes, and so on. Once this condition has been seen in a new engine, it is subsequently easy to identify. As the engine becomes older this coating takes on a black color, owing to the presence of soot.

Varnish coatings are apparently formed by the condensation of oil-gasoline vapors on new metal surfaces, and the more humid the climate, the greater the tendency toward varnish formation. The surface of a green engine probably exerts some catalytic influence to form these coatings from oil-gasoline vapors, but there are very few engines which do not have some varnish on the various internal parts. As a general rule, the first coat insulates the engine against further coatings, and there the matter ends for the great majority of internal-combustion engines.

If a new engine fails for some reason, this initial coating of varnish is likely to take the blame. Six months later the same failure would bring forth no mention of varnish because it would no longer be noticeable with its coat of soot. Engine varnish does not break piston rings, cause cylinder heads to crack, or pull the linings out of bearing shells. However, it is one more of the products which assist in causing piston rings to freeze in their grooves by acting as an additional binder for soot, oxidized oil, etc. Detergent-type oils are effective in preventing the formation of varnish on engine parts.

Effect of Fuel Dilution on Mineral Oils

When gasoline or fuel oil is mixed with a mineral oil, it will lower the S.A.E. number about one grade for each 5 per cent of fuel dilution. In the crankcase of a cold gasoline engine the fuel dilution caused by excessive "choking" may be quite high without doing any damage. If the dilution is 5 per cent upon starting the engine and the oil in use has a rating of S.A.E. 20, the effect will lower the rating to S.A.E. 10. But when the engine warms up, nearly all this dilution will evaporate very quickly. In very cold climates it is common practice to add gasoline to S.A.E. 10 oils in the crankcase of cold gasoline engines. This is the method by which aviation oils obtain a pour point of −65° F when diluted 30 per cent. These specifications were shown in Chapter 14. The 5-W oils usually eliminate the need for dilution.

If the engine is started and run for 20 minutes without load, little or no harm is done. Sometimes 15 to 20 per cent of gasoline must be added to frozen oil in the crankcase to enable the battery to turn the engine. Once started, the engine warms up, the oil thins down, and the gasoline evaporates. However, the best practice is to install suitable heating equipment for this type of operation.

Diesel engines present a more difficult starting problem in subzero surroundings because the fuel is heavier and does not flow easily. The pour point of an average paraffin-base No. 2 fuel oil is about 0° F, which is of no help if the temperature is −30 or −40° F.

For Diesels operating in very cold climates special winter fuels are often employed. They are manufactured from asphaltic-bearing crudes and have pour points down to −40 or −50° F. However, in extreme cases, the only satisfactory method of starting and operating Diesels is to install suitable heating equipment for the crankcase oil.

It is better to lower the viscosity of the crankcase oil by heating, rather than by a diluent. The table shows the effect of dilution on motor oils.

EFFECT OF KEROSENE DILUTION ON MOTOR OILS

S.A.E. Number	*Original Viscosity at 100° F*	*Per Cent Dilution with Kerosene*	*Approximate Viscosity of Mixture at 100° F*
10	250	5	170
20	420	5	300
30	670	5	500
40	1200	5	850
10	250	10	140
20	420	10	230
30	670	10	370
40	1200	10	640
10	250	15	110
20	420	15	170
30	670	15	270
40	1200	15	410

Cleaning Dirty Engines

The best method of cleaning a dirty engine is to dismantle, clean, and inspect all parts. If this is not warranted, solvent cleaning may be resorted to.

It must be kept in mind that solvent cleaning dislodges dirt which will circulate through the oil system. There is always the danger that a restricted oil passage will be blocked, with resulting engine damage.

There are many solvent compounds and cleansing mixtures on the market for cleaning internal-combustion engines. When this method is used to free piston rings and to dislodge sludge and deposits, care is required to prevent damage to the engine. The oil-pressure gage must be watched constantly.

An old-fashioned but powerful cleansing mixture consists of 60 per cent No. 2 fuel oil, 20 per cent S.A.E. motor oil, 10 per cent butyl alcohol, and 10 per cent toluene. With this mixture in the crankcase the engine should be allowed to idle for not more than an hour, and the crankcase temperature should be maintained as low as possible because this is a volatile mixture. However, at the end of the 1-hour idling run, there will be plenty of sludge in the crankcase; hence the oil pan should be dropped and the engine should be flushed out with a light oil before adding the regular charge of crankcase oil.

After dirty engines have been cleaned out, either with an oil and solvent mixture, or with a detergent-type oil, the engine will often become noisy and use more oil. This is because all moving parts have been freed of deposits, and not because the process has harmed the engine.

Bearings

Most bearing failures can be attributed to wear, corrosion, or fatigue. Bearing wear is prevented by thick-film lubrication, which is a function of viscosity. Marine engines, stationary Diesel, and aircraft engines are provided with oil coolers so that the viscosity can be controlled to provide thick-film lubrication. Most gasoline engines do not have coolers, so that at high engine output oil temperatures of 300° F result in thin-film lubrication. When the engine is operated on thin film, very small particles of dirt tend to abrade the bearing, with resulting wear. For this reason contaminates should be kept from the oil by oil changes and filters. Bearings also fail because of lack of oil, poor heat transfer, or fatigue.

The Babbitt metals are most susceptible to fatigue, and for this reason the alloy bearings have been developed. Fatigue failures are mechanical and in no way a lubrication problem. Among the advantages of a Babbitt bearing is its resistance to corrosion in engines.

Bearing corrosion is directly traceable to acidic-type compounds. The compounds are formed by fuel and oil oxidation. The rate of oxidation is accelerated by high temperatures, and the corrosive materials increase correspondingly. Considerable research has been carried out to find hard bearing metals immune to corrosion from this cause. High-grade Babbitt metal is unaffected by this action, but it is relatively soft and subject to fatigue, particularly in high-speed engines. Hence, copper-lead alloys and various combinations of a greater hardness are commonly employed to line bearings which must withstand high-speed operation, but they are not so well adapted to withstand the corrosive action of excessive petroleum acidity that results from oil oxidation.

Bearing corrosion can be recognized by an over-all pitting of all bearing surfaces. If it is allowed to continue too far, debris and loss of bearing area will cause complete bearing failure. If in a bearing failure corrosion is suspected, an examination of all the bearings will disclose whether or not corrosion was responsible.

Valve or Ring Sticking

Gum deposits from the fuel have a tendency to build up on the valve stem under the head on the intake valve. This interferes with the flow of gasoline to the cylinder, and in its worst form may cause sticking of valves. Because of the flow of air and fuel, the valves operate cool, and oil oxidation is not a problem. The exhaust valve runs very hot, and oxidized oil deposits form on the valve stem. These deposits may build up to the point where upon expansion of the valve stem the clearance may be taken up, and sticking occurs. Once wear has started on the valve stem guide, it progresses rapidly, as the exhaust gas finds its way between the valve stem and the bushing. In general, valve troubles are one of design, and little improvement can be expected by changing oils.

As an example, some engines limit the quantity of oil in the valve chamber to reduce oil consumption. High oil consumption is sometimes caused by oil's being drawn by the intake valve bushing, owing to the vacuum. Momentary smoking of the exhaust upon opening the throttle indicates adequate valve lubrication.

Lead deposits from burning fuel are found on various parts of the valve, and are another source of trouble. An analysis of some of these deposits is given in Chapter 29, under the heading "Effect of Lead."

Unstable oils can form varnishes and resins which cause rings to stick. An analysis of deposits taken from the ring groove will indicate if the deposits are from oxidized oil or are soot from combustion. If soot is the cause, a heavy-duty oil should be used to keep it dispersed. If oxidized oil is the cause, a more stable oil should be used. Sometimes sticking rings cannot be corrected by changing the fuel or oil; then the engine design should be investigated for the cause of the trouble.

Oil Consumption

The table shows the effect of road speed on oil consumption for a six-cylinder automobile engine in good mechanical condition.

Driving Speed Miles per Hour	*Miles per Quart*
30	800
40	700
50	600
60	300
70	150

The particular grade of oil has an influence on the rate of consumption, but the table is representative for average performance with an S.A.E. 30 oil. With lighter oils the rate of consumption would be higher.

This type of test is interesting to show the very small amount of oil that is actually burned in the cylinders, lost by distillation, or lost by leakage when operating conditions are normal.

Oil consumption is also influenced by the ability of an oil to resist the thinning effect of rising temperatures. Paraffin-base oils have superior qualities in this respect when compared with naphthenic oils. Hence, if two oils have the same viscosity at 100° F the oil containing the higher percentage of paraffin-base crude will generally show a lower rate of oil consumption.

The arbitrary measurement of this quality is termed "viscosity index," which is explained in Chapter 10, "Physical Tests."

Engines in poor mechanical condition may use excessive amounts of oil. A very rough rule is that one-third passes by worn valve guides, one-third passes by worn piston rings, and the remainder by an excessive amount of oil's being thrown onto the cylinder wall by loose connecting rod bearings.

Low-viscosity oils increase oil consumption while decreasing friction and fuel consumption. With high-price fuels, this may influence the choice of viscosity and the resulting oil consumption.

Analyses of Used Crankcase Oils

The following are examples of used oil analyses with explanatory notes.

Marine Diesel: 2 cycles, pump-scavenged, 300 rpm, 800 horsepower, 7 cylinders. Force-feed oiling system to bearings and oil cooler installed. Mechanical lubricator for cylinder supply. Straight mineral S.A.E. 40 paraffin-base oil used throughout. Fuller's earth type of filter with heater to purify the lubricating oil. Samples taken before and after filtration.

	New Oil	*After Filtering*	*Before Filtering*
Service hours	....	700	700
Flash °F (open cup)	445	410	400
Saybolt viscosity at 100° F	630	615	605
Saybolt viscosity at 210° F	72	69	68
Per cent ash	....	....	0.03
Per cent moisture	....	....	....
Neutralization number	0.07	0.15	0.19
Per cent insoluble in naphtha	....	0.28	0.35
Per cent insoluble in benzol	....	0.12	0.15
Per cent oxidized oil	....	0.16	0.20

This sample shows that the oil was in good condition and was suitable for continued use. Normal dilution with fuel oil was indicated by a drop in the flash point and lower viscosity. The rise in acidic compounds due to oxidation was normal, as indicated by the rise in neutralization number. The percentage of oxidized oil was the difference between the per cent insoluble in naphtha and the per cent insoluble in benzol, or 0.16 per cent, which was not excessive. The per cent insoluble in benzol was of a nonabrasive nature, probably soot. This analysis clearly demonstrates the advantage of adequate filtering equipment for Diesels.

Had the viscosity shown a pronounced drop of 100 seconds or more it would have indicated fuel dilution and injector trouble. This would of course be verified by a corresponding drop in the flash point. Had the per cent ash been above 0.1 per cent it would have indicated an excessive amount of noncombustible and abrasive materials, such as worn metal. Had there been water in the oil it would have been due to too low operating temperatures in cylinder wall or similar obvious cause. Had the neutralization number been 1.0 or above it would have indicated excessive acidity due to oxidation or aging of the oil charge. This last condition would have been reflected by a higher viscosity reading and a greater percentage of oxidized oil.

Marine Diesel: 2 cycles, double-acting, pump-scavenged, 92 rpm, 5000 horsepower, 4 cylinders. Oil-cooled pistons. Force-feed oiling system to bearings and oil coolers installed. Mechanical lubricator for cylinder supply. Straight mineral, mixed-base oil, S.A.E. 40, used for cylinder lubrication; straight mineral S.A.E. 30 mixed-base oil used for bearing lubrication. Centrifuge employed for purifying the charge.

	New Oil	*Before Centrifuging*	*After Centrifuging*
Service hours	....	1400	1400
Flash °F (open cup)	425	425	425
Saybolt viscosity at 210° F	64	65	65
Per cent ash	. .	Trace	Trace
Per cent moisture	....	Heavy trace	None
Neutralization number	0.06	0.28	0.28
Per cent insoluble in naphtha	....	0.20	0.17
Per cent insoluble in benzol	....	0.17	0.15

This oil charge was being subjected to contamination with water which the centrifuge was removing. Otherwise the oil was in good condition.

The following analysis shows the effect of high crankcase temperatures. The engine was a four-cycle design of the automotive type which developed 95 horsepower at 1900 rpm. The oil in service was a straight mineral S.A.E. 30 grade manufactured from a mixed-base crude.

	New Oil	*Used Oil*
Service hours	....	400
Saybolt viscosity at 100° F	450	980
Neutralization number	0.07	5.3
Ash	....	0.38

This particular engine was being operated with a heavy overload, and the oil filter had been removed. The sample contained a high percentage of sludge, which is obvious from the rise in viscosity and neutralization number. The ash was composed for the most part of metallic particles as a result of wear. The amount of new oil added was about 1 gallon every 2 hours.

This example represents Diesel operation at its worst. Nevertheless, it is an object lesson in the punishment that Diesels can withstand. But in all cases of this sort carbon deposits in the piston rings act as a governor. When compression becomes too low to fire the fuel charge, as a result of stuck rings, the engine will stop automatically. Not until the piston rings have been cleared of carbon will the engine start; and, since this necessitates an overhauling job, the engine is generally spared from material damage.

Suitable Lubricants for Diesel Engines

When confronted with the problem of selecting a suitable type of lubricating oil for a Diesel engine, operating engineers are nearly always in a quandary for the reason that all sorts of claims are made for different brands. Hence, the operating engineer generally experiments with different brands on his own account to try to find a particular grade that will give the minimum amount of trouble from carbon deposits behind the piston rings. This problem is common to all engines of the internal-combustion type, and applies especially to Diesel engines. As a result, operating engineers are more interested in avoiding these deposits than in any other single phase of Diesel-engine operation.

Unfortunately there is no oil made that will entirely eliminate this problem in Diesel-engine cylinders. Straight mineral oils have about reached the point where their behavior in different types of Diesel engines is reasonably well known, and little improvement can be anticipated without the aid of special additives, or new discoveries in the synthetic field that will impart properties not now possessed by straight mineral oils. This matter is discussed in Chapter 22 under the heading "Additives."

Gasoline engines of the automotive type have been fairly well standardized because millions have been built for one purpose only. Not so the Diesel engine; from small engines of 4 or 5 horsepower they range all the way up to 25,000 horsepower, and design features, particularly those which control combustion, are varied and numerous.

The main factor which makes cylinder lubrication a problem in Diesels is the high operating temperatures, and in small high-speed engines the additional factor of soot production. In the trunk-piston type of engine, wherein the crankcase oil is splashed onto the cylinder walls from the bearings, there is of course the added factor of crankcase sludge lodging behind the piston rings to accelerate the formation of gummy deposits and ring sticking. However, high temperature is the principal condition which has to be met in lubricating Diesel-engine cylinders.

The authors have examined many Diesel engines of all types, both land and marine, and many laboratory analyses of used oils, carbon deposits, and crankcase sludges, only to arrive at a very simple and general conclusion. For large engines equipped with mechanical lubricators to feed oil to the pistons, the benefits of paraffin- and mixed-base-type oils may be secured if the oil supply to each cylinder is cut to a lower rate of feed than is generally permissible with naphthenic-type oils. Sight holes are provided in the great majority of the larger engines for examining the piston rings. The most desirable rate of feed may be gaged by the condition of the top ring, whether it is wet, moist, or dry. The best condition is moist. Another check is to examine the exhaust valves or ports, depending upon the engine design. They should be just moist with oil.

While carrying out an exhaustive investigation of several Diesel ships, it was found that with straight mineral- and detergent-type S.A.E. 30 and S.A.E. 40 mixed-base oils in service the average cylinder-feed rate from the mechanical lubricators could often be reduced below the amount recommended by the various manufacturers of the Diesel engines, sometimes to nearly half the amount. Furthermore, operating results as judged by piston ring deposits, which were examined at the time of each annual overhaul, were very satisfactory. From these observations it is obvious that consideration must be given to the type of oil in use. These particular engines were of various designs, including two-cycle designs with pump scavenging, and the horsepowers ranged from 800 to 5000.

Large two-cycle engines, designed with crankcase scavenging and using a straight mineral oil, generally operate better when supplied with the naphthenic type of oils, because in this design oil mist from the crankcase is drawn into the cylinders with the scavenging air and burned with the fuel. Under these conditions the lower carbon content and softer type of carbon produced by naphthenic oils is advantageous in overcoming the disadvantage of partially burning a small but continuous quantity of lubricating oil.

Diesels operating on the four-stroke cycle approach the conditions which prevail in gasoline engines, and, as a general rule, naphthenic mixed-base and paraffinic oils give equally satisfactory service. When the engine cylinders are lubricated by oil thrown from the revolving crankpin bearings, the piston wiper rings must be maintained in good working condition when using straight mineral paraffin-base oils. Otherwise, not only are the benefits of the higher heat-resisting qualities of this type of oil lost, but the excessive supply which passes the wiper rings will tend to produce carbon.

The additives now employed in manufacturing Diesel lubricating oils have overcome much of the trouble that used to result from hard carbon formations, particularly formations which caused piston rings to freeze in their grooves. Additive-type oils have already been discussed in Chapter 9.

In all Diesel operations the lubricating oil should be as light as possible for the reason that the lighter the oil, the lower the carbon content and the less tendency to form deposits. Lubricating oils above the S.A.E. 40 grade are, as a rule, too heavy for cylinder lubrication, even on the largest engines. If satisfactory lubrication is found difficult with the larger cylinder sizes, the addition of extra leads from the mechanical lubricator will generally accomplish more than the use of heavier oils.

When the engine is equipped with a separate oiling system for bearing lubrication the Saybolt viscosity of the oil should not be under 450 seconds at 100° F, S.A.E. 30, for most large engines because with these designs it is a simple matter to favor the bearings. When the crankshaft speed is about 100 rpm, as, for example, on marine engines, the bearing oil should not be under 550 seconds at 100° F. In fact, for this general type and class of large engine the bearing oil should have a Saybolt viscosity of about 750 to 950 seconds at 100° F, S.A.E. 40 to 50. This matter is governed largely by the speed of the crankshaft and temperature of oil. However, it must be borne in mind that at low rotational speeds the formation of a strong oil film is controlled mainly by the viscosity of the oil, and these suggestions are a guide.

Diesel-engine manufacturers issue instructions covering the viscosity or S.A.E. number of the lubricating oil best adapted to a particular engine model, but formulas for the procedure to be followed in manufacturing the oil are issued by only a few companies. These recommendations generally cover instructions on the use of detergent-type oils, and the procedure has been found beneficial and adaptable, particularly where the engines are not equipped with effective cooling and oil-purifying devices, such as may be installed in engine rooms but would be out of the question on small engines of the automotive type. See Chapter 9, "Additives."

To set down a series of specifications that would be a guide to the most suitable lubricating oils for various types of Diesels might seem a relatively simple task, but actually it is extremely difficult, if not impossible. However, the following comments may be of assistance.

Paraffin-base oils possess greater heat-resisting properties than any other type of straight mineral oil, but the carbon formed by distillation is correspondingly hard. Hence, in the past, naphthenic-base oils were somewhat favored for Diesel engines on account of the lower initial carbon content and the softer type of carbon formed when decomposition took place in the cylinders. This, in brief, sums up the old controversy of paraffin- and mixed-base oils versus naphthenic-base oils for Diesel-engine lubrication. The question was never settled with any degree of satisfaction, and to a decreasing extent the subject is still a matter of debate.

Antioxidation compounds and carbon-dispersing compounds came into use during the years 1935 to 1940, and since that time these additives have been perfected to a point where they are of proved benefit in lubricating oils for internal-combustion engines. For this reason the old controversies of carbon formatives are not so much in the forefront of lubrication debates, particularly when the discussion centers on the smaller high-speed types in which these oils are in almost universal use.

Lubricating Oils for Gasoline Engines of the Automotive Type

The S.A.E. 5W to 50 will cover all automotive engines and operating conditions. Most passenger cars can be lubricated with S.A.E. 10 or 20 oil. The well-lubricated engine will use some oil. Should the oil consumption be excessive some slight improvement can be made by going to a heavier grade of oil; likewise, if no oil is consumed a lighter-viscosity oil should be used. When engines are fitted so tightly that there is no oil consumption, the engine efficiency is likely to be poor and excessive gasoline is used. The proper selection of lubricant viscosity will save from 2 to 4 per cent in fuel consumption. This savings in fuel helps to offset the slightly higher cost of adequate lubrication.

Contrary to public opinion, cars that accumulate mileage rapidly require less frequent oil changes than those with low mileage service. When engines are driven steadily, crankcase dilution and condensation are held to a minimum. Crankcase breathing is effective only over 30 mph, when the entire engine becomes warm and lubrication becomes more effective.

Where filters are employed the cartridges should be changed regularly. The contaminates lodging in the filter are catalysts, and putting new oil through the filter accelerates its breakdown. Tests have shown that engines in which the filter cartridges were not changed were in worse condition than engines that did not employ filters.

Lubricating Oil for Aircraft Engines

Aircraft-engine oil specifications were outlined in Chapter 14, "Specifications." Aircraft engines differ from automotive engines in that they operate under high load continuously, and under light loads only for warming up. The oil recommended for an engine type should be adhered to, as there is a minimum viscosity which will provide thick-film lubrication for the bearings.

Aircraft engines are equipped with oil coolers in order to maintain the proper oil viscosity under any operating condition.

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Heat Treating Oils

Steel is not a single element but a complex artificial product composed of iron and other elements held in the solid mass as a mixture of alloys and chemical compounds. It is possible to change materially the properties of steel by heating and cooling it under controlled conditions, a process known under the general term of "heat treatment." There are numerous processes for obtaining certain desired properties by various methods of heat treatment, but from the standpoint of petroleum products two of the methods are known as "quenching" and "tempering."

Quenching Oils

When steel is heated there is a definite temperature at which a marked change in its structure occurs. This point is known as the critical temperature, and if the steel is slowly cooled the process is reversed and the steel regains its original structure when cold. However, if the steel is heated to a temperature above its critical temperature and is suddenly cooled by immersion in a liquid bath, it does not return to its original structure but instead is hardened or toughened. This operation is known as "quenching" or "hardening."

The critical temperature of straight carbon steels ranges from about 1300° to 1500° F, and for alloy steels it is as high as 2300° F. However, the carbon content and rate of cooling influence the final structure of the steel. This is entirely a metallurgical problem. Water and emulsions of oil and water are often used for quenching low carbon steels, but for alloy steels this method cools the metal too rapidly, making it hard and brittle. For medium and high carbon steels the quick cooling provided by water, or salt and water solutions, causes excessive brittleness, and the strains set up may cause warping or cracking. In addition, the cooling rate of water decreases rapidly as its temperature rises, and, unless the bath is held at a constant temperature, the final structure of different pieces of the same steel will vary. Also, bubbles of steam, caused by the boiling of water adjacent to the hot steel, may adhere close to the metal and cause variations in the rate of cooling and spots of different hardness.

Mineral oil has a specific heat of about 0.45, and water 1.0; thus mineral oil is not greatly affected by variations in temperature. This makes it a very suitable quenching medium for all sizes of medium and high carbon steels and for large and irregular shapes of any steel. The excessive stresses set up by quenching in water are not developed.

The critical temperature to which most steels must be heated before quenching is above 1300° F, and the oil used for cooling should be of fairly good quality to minimize oxidation and the formation of deposits. Also, the oil should be sufficiently low in viscosity so that convection currents will conduct the heat away from the metal. Oils too high in viscosity are sluggish, with the result that the portion of oil adjacent to the hot metal is not removed quickly by convection currents, and therefore vaporizes and carbonizes. On the other hand, the oil cannot be too fluid because the low boiling range of very thin oils results in excessive vaporization losses. Mineral oils having Saybolt universal viscosities ranging from 100 to 200 seconds at 100° F have been found most suitable for this service.

Fatty oils such as fish and animal oils have a slightly lower cooling rate than mineral oils but are not ideal for quenching because of their greater tendency to oxidize and thicken. However, in some instances blends of mineral oils with 3 to 5 per cent of a suitable fatty oil are used; such products are believed to have a slightly lower and more uniform cooling rate than straight mineral oils of the same viscosity. Owing to the fact that fatty oils and other wetting agents have lower surface tensions, they are also believed to creep and aid in dislodging vapor bubbles which may tend to stick to the side of the hot metal.

Oil Circulation

Large quenching baths may contain several hundred gallons of oil, and for these larger systems it is common practice to circulate the oil from the tank to a cooler and back to the tank. This circulation of oil permits a close control over its temperature, which in turn results in more uniform cooling of the metal being quenched. Circulation of the oil also disrupts the formation of vapor bubbles on the metal, which is an important consideration because it has an influence on uniform quenching.

Quenching Oil Temperatures

From results secured by experimenters, most authorities seem to prefer quenching oil temperatures between 85 and 125° F. However, this again is a metallurgical problem, and sometimes temperatures up to 160° F are employed to further slow up the cooling rate.

Tempering Oils

Tempering, which is the process employed to reduce the internal strains set up in the quenching or hardening treatment, consists in heating the metal to a definite temperature *below* its critical point, then cooling it gradually. Large pieces of metal are usually tempered in a drawing furnace, but oil baths are generally used for smaller pieces.

In the tempering process the heated metal pieces are placed in an oil bath which is also heated to a desired temperature, usually between 400° and 600° F, depending upon the composition and the final properties desired. After the steel pieces have been immersed in the oil bath, the oil and metal are allowed to cool slowly, thereby reducing or eliminating internal strains.

Because the oil is heated to a relatively high temperature, it should be of high viscosity, with a flash point above the maximum temperature to which it is subjected. Cylinder stocks of high viscosity are used for this service, and paraffin-base oils are most suitable because of their high flash and fire points and inherently good resistance to oxidation and consequent sludging.

Quenching and Tempering Recommendations

Quenching	*Tempering*
Saybolt viscosity of mineral oil 100 to 200 sec at 100° F, with or without 3 to 5% of lard oil.	Saybolt viscosity of mineral oil 250 to 300 sec at 210° F, minimum flash point 600° F.

Note. Oils increase in viscosity as they oxidize; therefore, depending upon the requirements of the finished steel, samples of the oil should be tested and viscosity readings checked.

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Cutting Oils

A cutting oil performs three primary functions: it acts as a coolant; it carries away small particles formed in machining or grinding operations; and it provides lubrication between the tool and the work.

Water is plentiful and inexpensive and has excellent cooling properties. It is, therefore, used extensively in cutting and grinding fluids. Oil is only four-tenths as effective as water as a coolant but has excellent lubricating values. In compromising between oil and water as lubricants and coolants, there are an infinite number of mixtures which can be compounded.

The cutting oils flowing over the work and tool carry and wash away the debris from the metal-working operations.

Composition of Cutting Oils

Cutting oils are of five general types:

1. Alkaline solutions, which consist of a mild alkaline compound mixed with water. This type is generally confined to grinding operations, where cooling and the laying of dust are more important than lubrication.

2. Soluble cutting oils, which are composed of mineral oils that have been compounded with emulsifying materials to make them miscible in water. Soluble oil-and-water emulsions are used in metal-cutting operations when cooling requirements predominate. This type of cutting oil produces stronger oil films than alkaline solutions. They are cut back with water in various proportions, depending upon the cutting operation. They may also contain a percentage of sulfur to impart extreme-pressure properties.

3. Straight mineral oils of light body, which are suitable for light-duty cutting where both lubrication and cooling are desired. This type of cutting oil is used extensively for cutting such metals as magnesium and nonferrous metals.

4. Fatty oils, such as lard oil, which is generally blended with a light mineral oil. Mineral-lard oil blends have been largely replaced by more powerful sulfurized oils, but they are still used to some extent for cutting copper and copper alloys where tarnish is an important consideration. This factor arises when a tinning or plating operation is to be carried out later. Fatty oils tend to become rancid, and when this occurs the odor is objectionable. Hence they are seldom used straight.

5. Sulfurized- and chlorinated-base oils, which are blended with mineral oils and produce "metallic film" lubrication when "fluid film" lubrication is destroyed by extreme pressures on the chip bearing surfaces of cutting tools.

Soluble Cutting Oils

The art of making mineral oils soluble in water is to secure a finished product that will form a permanent emulsion. If all waters were "soft" and uniform, as is rain water, the problem would be relatively simple, but water is a powerful solvent and may contain materials which make it "hard" and resistant to saponification. Hence the ingredients employed in manufacturing soluble oils are selected with a view to imparting solubility in "hard" waters and at the same time avoiding ingredients of a corrosive nature.

An important requisite of all formulas is that the ingredients must be available in large quantity and at reasonable cost. Sludge-base extracts and soap emulsifying liquids are extensively used for this reason. Sludge-base extracts, sodium sulfonates, are manufactured from the acid sludge that is recovered as a byproduct when refining lubricating oils with sulfuric acid. This type of base is very effective, simple to use, and extensively employed in metal cutting soluble oils. The following are a few examples of approximate formulas for soluble oils.

1.	Sodium sulfonate base	12%
	Pale mineral oil (viscosity 100 S.U.S. at 100° F)	88%
2.	Sodium sulfonate base	12%
	Pale mineral oil (viscosity 100 S.U.S. at 100° F)	80 to 85%
	Other materials, including small percentages of diethylene glycol, which is an antifreeze compound.	
	Sulfur compounds which assist in imparting extreme properties.	
	Water-white rosin oil, caustic soda, and other products which stabilize the emulsion, retard corrosion, etc.	3 to 8%

3.	Pale mineral oil (viscosity 100 S.U.S. at 100° F)	80%
	Blown rapeseed oil	8%
	Degras	5%
	Potash	3%
	Rosin oil (water white)	4%

4. Rosin oil may be saponified with water and borax, then cooked until the water is evaporated. The soap solution will take up mineral oil in the approximate proportions of 2 pounds of borax and 1 gallon of rosin oil for every 1½ gallons of light mineral oil.
5. Oleic acid may be saponified with water and sodium hydrate, then cooked to soap and clarified with wood alcohol. The mineral oil is then added and taken up by the soap solution.
6. Another group, known as grinding compounds, consists of emulsifying soaps with good rust-resisting properties, as, for example, potassium oleate.

The purpose of an emulsion is to secure maximum cooling with water, retard rusting, and at the same time impart some lubricating properties to the coolant, so that friction is reduced between the moving chip and the contact surface of the cutting tool.

In addition to the various types of prepared emulsifying bases and soaps, there are of course special materials which may be compounded in soluble cutting oils. For example, sulfur compounds may be used in soluble oils to impart a degree of extreme-pressure effect between the chip and the contact surface of the cutting tool. There are also transparent-type soluble cutting fluids which do not contain any mineral oil but only an extreme-pressure compound.

Mixing an Emulsion

When mixing a soluble oil with water, the correct practice is to pour the oil into the water. Not only does this procedure make the mixing process easier, but the emulsion is made homogeneous and permanent. Pouring the oil into the water and gently stirring at the same time assures an "oil-in-water emulsion," which is the desired state of equilibrium.

Use of Water Softeners

Hard waters sometimes render oil and water emulsions unstable and the water may have to be softened before the emulsion is made. When rusting is caused by a hard water, the use of soda ash or trisodium phosphate will soften the water and very often overcome the difficulty. As a general rule, not more than 8 pounds of either material per 100 pounds of water will be sufficient.

Light Mineral Oils

Mineral oils, particularly those employed for blending with base oils, are generally of the light spindle type having Saybolt viscosities between 40 and 150 seconds at 100° F. In some cases where maximum fluidity is required, the lightest oils are employed for blending purposes, as, for example, when diluting compounded-base oils for cutting aluminum and similar light alloys.

Straight mineral oils are occasionally used for machining copper, brass, bronze, etc., but, where a cutting fluid of this type is required, the more effective practice is to blend the mineral oil with lard oil or a small amount of compounded-base oil to improve lubrication between the flowing chip and the tool.

Mineral-Lard Oils

Mineral-lard oils are blends of mineral and lard oil in various proportions, as, for example, 10, 20, 30, 40, and 50 per cent of lard oil. This type of cutting oil generally has a Saybolt viscosity of about 150 to 200 seconds at 100° F, which is controlled by the viscosity of the mineral oil. The viscosity of lard oil is approximately 100 seconds at 100° F.

Mineral-lard oil combinations have been largely displaced by sulfurized and chlorinated cutting oils. However, mineral-lard oil is sometimes employed for cutting copper and copper alloys if tarnish is an important consideration prior to a tinning or plating process, but under ordinary conditions some of the better-grade base oils are nontarnishing for all practical purposes when blended with light mineral oils.

The presence of lard oil assists in lowering the effect of friction by imparting mild extreme properties between the moving chip and the surface of the tool. When chip pressures are very moderate, this type of cutting oil gives reasonably good results. As a general rule, the maximum effective amount of lard oil is about 30 per cent. More than this does not appear to produce any further benefit.

Sulfurized and Chlorinated Cutting Oils

The purpose of adding sulfur, chlorine, and similar materials to mineral oils is to provide microscopic films of metallic oxides when the oil film breaks down between the chip and the cutting tool. These films are produced by the action of high temperatures, and they prevent welding. If steel is being cut and the oil contains sulfur, iron sulfide is formed, while chlorine compounds produce iron chloride. In either case the results are similar, and metallic lubrication is substituted for fluid-film lubrication.

Depending upon the source of the crude and upon the refining methods employed for purification purposes, straight mineral oils may contain relatively high percentages of chemically combined sulfur. In fact, mineral oils are obtainable with a naturally combined sulfur content of 4 per cent. However, in this form the sulfur has very little value in cutting oils. Hence for controlled compounding purposes, and to secure cutting oils with transparent properties, sulfur is first cooked into and bonded with a fatty oil, such as sperm oil or lard oil, and the compound is added to the mineral oil. Sulfur may also be added directly to mineral oils by the aid of heat. Compounded oils of this latter type are opaque and black. They are inexpensive and have good properties for rough metal cutting, as, for example, pipe threading. The maximum amount of sulfur that can be directly cooked into a mineral oil without the aid of a fatty oil or other bonding material is about 3 per cent. The maximum amount of sulfur that can be bonded with a fatty oil is about 15 per cent.

Chlorine is a highly active, pungent, and poisonous element which also reacts very easily to form compounds of chloride with mineral, animal, vegetable, and fish oils, and a vast number of other materials, including coal-tar products.

Like sulfur, chlorine is used in mineral oils to impart extreme-pressure properties. For this purpose chlorine is first of all chemically compounded with another material, generally a fatty oil, and is then blended with the mineral oil. This method allows an accurate control of the blending process and simplifies the manufacturing procedure.

While many chlorine compounds such as carbon tetrachloride possess phenomenal properties when used for cutting metal, they unfortunately produce toxic chlorine gases during the process of chemical reaction; consequently they cannot be used for practical applications in machine shops. Apart from this, the particular medium, carbon tetrachloride, evaporates quickly, thus providing refrigeration, but it is highly toxic and should not be used.

Machine operators sometimes carry a bottle of carbon tetrachloride in their pockets, because 1 or 2 per cent of this material in the cutting oil will produce startling beneficial results. However, chlorine in this form presents a danger of injury to health. The chemical reaction at the tool produces the deadly phosgene gas.

However, in actual cutting operations employing less active and more suitable chlorine compounds, so little chlorine is employed and so little is used up over a period of days that no toxic effect from the cutting operation is possible.

According to some observers chlorine compounds tend to dislodge materials employed to braze hard tips onto cutting tools, as, for example, carbide tips. This objection, i.e., dislodging tips, is also raised with sulfurized oils, but many observers seem to think that this action is very often due to high temperatures or fatigue of the binder rather than to any action on the part of the cutting oil.

Carbide tips allow high cutting speeds and high tool temperatures. For this reason a soluble oil-and-water emulsion is often required to maintain the necessary cooling effect. However, there is no advantage in attempting to use emulsions on carbide tips if the particular operation requires an oil containing extreme-pressure properties.

The following are examples of cutting oils employed in machine shops.

1.	Saybolt viscosity at 100° F	150 sec
	Color	Black
	Sulfur (added)	3%

This is an example of a cutting oil wherein the sulfur has been added directly to the mineral oil with the aid of heat. This type of oil is very active for cutting purposes. It is commonly used for pipe threading where obliteration of the view of the operation by the black color is no handicap.

2.	Saybolt viscosity at 100° F	150 sec
	Color	Black
	Fatty oil	5%
	Sulfur (added)	4%

This cutting oil is similar to No. 1, but it is more stable on account of the bonding action secured with the aid of a little fatty oil. This type of oil may also contain a small percentage of bonded chlorine.

3.	Saybolt viscosity at 100° F	130 sec
	Sulfur (added)	2%
	Lard oil	13%
	Mineral	85%

This is an example of a sulfurized-base oil after blending with a light mineral oil. The color will be light enough to permit viewing the cutting operation in the machine.

4.	Saybolt viscosity at 100° F	130 sec
	Sulfur (added)	2%
	Sperm oil	18%
	Mineral oil	80%

This is another example of a sulfurized-base oil after blending with a light mineral oil. The color will be light enough to permit viewing the cutting operation in the machine.

5\.

Saybolt viscosity at 100° F	130 sec
Sulfur (added)	1%
Chlorine (added)	1%
Fatty oil	18%
Mineral oil	80%

This is an example of a sulfurized-chlorinated-base oil after blending with a light mineral oil.

Other Combinations

Many different blends are of course possible with base oils. The foregoing are merely average combinations. For viscosity blending purposes an A.S.T.M. chart is generally employed. These charts are published by the American Society for Testing Materials.

The selection of a suitable cutting oil for a particular operation is an important factor in production. In large machine shops the knowledge, skill, and experience required to standardize suitable cutting-tool designs, organize uniform practices in tool grinding and honing, is an exacting task which has a far-reaching effect on tool life, and finish on the workpieces.

In the selection of cutting oils for various operations, the general rule is to employ an oil-and-water emulsion for maximum cooling effect and a compounded mineral oil of the chemically reactive type when maximum lubrication between chip and tool is required. For example, broaching operations carried out on steel workpieces produce heavy shock loads on cutting tools, speeds are of necessity slow to maintain these shock loads at a minimum, and pressures run high between the chips and tool faces. If a mixture of soluble oil and water were used, the shock loads would not be damped down, and the heavy chip pressures would eliminate any chance of maintaining a normal film of lubricating oil between the chips and the tool faces. Hence, excessive built-up edges would form, welding actions would occur, and the emulsion would maintain only a comparatively ineffective cooling action. In actual practice this particular operation requires a copious supply of heavy mineral oil to damp down the shock loads as much as possible and a relatively high percentage of chemically reactive material to provide microscopic lubricating films of metal oxide on the bearing areas of the tool faces.

The other extreme is found in machining cast iron, as, for example, in planing operations. This metal produces a small segmental chip which crumbles ahead of the tool and exerts very little pressure from chip flow on the face of the cutting tool. Hence the benefit of a cutting oil is relatively small, and cast iron is generally machined dry. Where it is convenient, the tool may be maintained at a lower temperature by the application of a weak oil-and-water emulsion. The finish on the workpiece and the life of the tool are sometimes improved by this additional aid.

An intermediate example is that of grinding. Here a weak solution of soluble oil and water is employed to lay the dust, retard corrosion, and, to some extent, produce a smoother finish.

Between these three applications there are many possible recommendations, and sometimes there are "borderline" applications where it is difficult to judge the most suitable type of coolant without resorting to trial-and-error methods. For example, milling operations on some grades of steel require a soluble oil for best results, but the same operation carried out on a slightly different alloy may require a mineral oil containing a reactive compound. Very often a change in cutting speed, or a change in the design, or grinding of the cutting tool will alter the chip formation and influence the recommendation. Problems of this type have to be solved individually.

There is no exact formula that may be used for arriving at definite recommendations with cutting oils. The great majority of applications are based on practical experience, but in many shops two or three cutting oils suffice to cover the requirements of several hundred machine tools. However, it is possible to employ unsuitable mixtures or blends. For example, if too much oil is used in a grinding emulsion, the excess oil will plug the pores of the wheel and cause it to skid instead of grind.

Then again—and this is very important—*if a compounded mineral oil of the extreme-pressure type is being employed for high-speed cutting operations the percentage of chemically reactive material must not be excessive.* When a high rate of chemical reaction is maintained on the face of a cutting tool, the effect will often reduce the service life of the tool rather than impart any beneficial effect. If the active ingredient is sulfur and the workpieces are made of steel, this effect is apparently caused by the formation of too much iron sulfide, which becomes abrasive.

The tables given here are a few examples of approximate cutting oil recommendations employing sulfurized oils. Where blending is practiced with a base oil, the viscosity of the blend is controlled by the mineral oil and the percentage of sulfur is controlled by the proportion of mineral oil.

For example, if a base oil contains 10 per cent of sulfur and the desired cutting oil is to contain 2 per cent of sulfur, the proportion of mineral oil in the blend would be $(10 \div 2) - 1$, or 4 parts of mineral oil and 1 part of base oil.

The reader should understand that the recommendations are very general and rather broad, for the reason that cutting operations vary considerably.

APPROXIMATE RECOMMENDATIONS FOR MACHINING STEEL AND STEEL ALLOYS *

Operation	*Saybolt Viscosity at 100° F*	*Per Cent Sulfur or Equivalent Material*
Broaching	300 to 500	4
Tapping	125 to 300	2 to 4
Threading	125 to 300	2 to 4
Hobbing	125 to 300	2 to 4
Milling (rough)	Soluble oil	Emulsion
Milling (normal)	125 to 300	½ to 2
Drilling (heavy)	100 to 200	½ to 2
Drilling (normal)	Soluble oil	Emulsion
Reaming	100 to 200	½ to 2
Turning	Soluble oil	Emulsion
Automatic screw machines	100 to 200	½ to 1

* As a general rule the higher the cutting speed, the lower the percentage of reactive element and the lower the viscosity of the oil.

APPROXIMATE RECOMMENDATIONS FOR MACHINING COPPER AND COPPER ALLOYS *

Operation	*Saybolt Viscosity at 100° F*	*Per Cent Sulfur or Equivalent Material*
Broaching	100 to 150	1 to 2
Tapping	75 to 140	½ to 1
Threading	75 to 100	½ to 1
Hobbing	75 to 140	½ to 1
Milling	75 to 140	½ to 1
Drilling	75 to 140	½
Reaming	75 to 140	½
Turning	Dry or soluble oil	. . .
Automatic screw machines	75 to 125	½ to 1

* For mineral-lard oil blends the general practice is to use about 10 to 20 per cent of lard oil and a Saybolt viscosity of 150 to 225 seconds at 100° F for the finished blend.

APPROXIMATE RECOMMENDATIONS FOR MACHINING ALUMINUM AND MAGNESIUM *

Operation	*Saybolt Viscosity at 100° F*	*Per Cent Sulfur or Equivalent Material*
Broaching	40 to 100	½ to 1
Tapping	40 to 60	½ to ¾
Threading	40 to 60	½ to ¾
Milling	40 to 60	½
Drilling	Soluble oil †	Emulsion
Turning	Soluble oil †	Emulsion
Automatic machines	40 to 60	½

* When machining magnesium use the lighter-viscosity blends. Soluble oil-and-water emulsions should not be used when machining magnesium, on account of the fire hazard. Magnesium will react chemically and burn with water at high temperatures and increase the fire hazard.

† Optional, for aluminum.

APPROXIMATE RECOMMENDATIONS FOR GRINDING

Type of Grinding	*Type of Oil*	*Mixture with Water*
Centerless	Soluble	1 to 50
Cylindrical	Soluble	1 to 80
Surface	Soluble	1 to 100

The Built-Up Edge

In all metal-cutting operations considerable influence is exerted on the quality of the cut by compressed fragments of metal which build up at the tip of the cutting tool. This condition is illustrated in Fig. 1, which is greatly enlarged to show the formation of these compressed fragments. This built-up edge breaks down intermittently at the forward end, then builds up at a rapid rate, thus covering the surface of the workpiece with a multitude of fragments.

These breaking fragments produce roughness on a machined surface, the degree of roughness depending largely upon the size of the built-up edge and, of course, upon the size of the fragments intermittently breaking off. Built-up edges are undesirable not only from the viewpoint of finish but from the viewpoint of heat transfer between cutting tool and coolant. When built-up edges are allowed to bond and anchor permanently on the tip of a cutting tool, the sharp edge is correspondingly replaced with a blunt edge of the compressed fragments. This effect raises the heat of friction, scuffs the tool, and very often causes spotty hardening on the surface of the workpiece.

Built-up edges cannot be eliminated entirely from cutting operations, but they may be controlled and greatly reduced by grinding and polishing the contact surfaces of the tool to reduce friction, by eliminating long curling chips with a chip breaker, by cutting down on excessive tool rakes, and by other methods such as the selection of a coolant adapted to the operation.

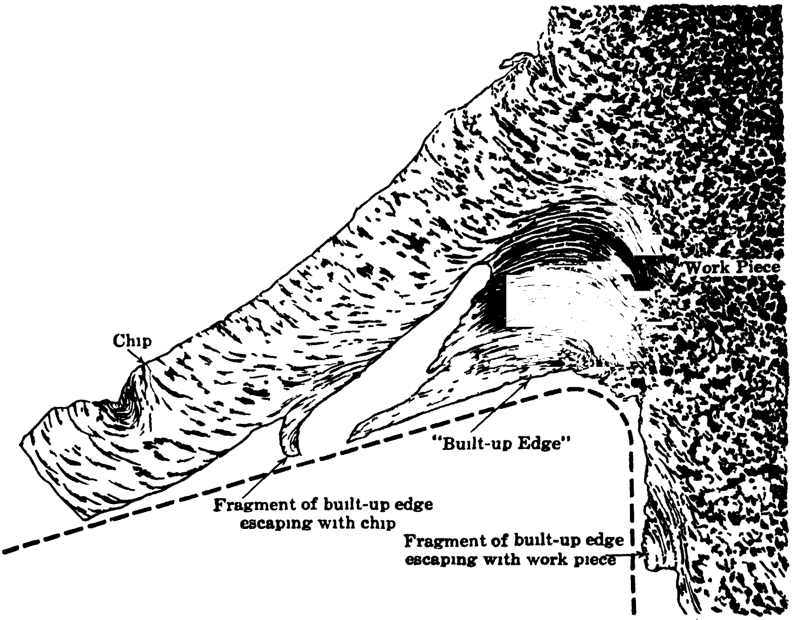
Work Piece
Chip
"Built-up Edge"
Fragment of built-up edge escaping with chip
Fragment of built-up edge escaping with work piece

FIG. 1. Diagram of a built-up edge on the front of a cutting tool. The size of the built-up edge is exaggerated for the purpose of illustration.

The success of carbide tips and of hard, polished cutting materials is largely due to reduced friction between chip and tool. This feature, and the high cutting speeds obtainable, lower fragmentary build-up and result in a superior finish on the workpiece.

When cutting tools are ground and finished to a smoothness of about 5 microinches (5 millionths of an inch), the length of useful service is extended to a point far beyond the limit that may be secured with hand-ground tools. An average hand-ground tool has a roughness of about 20 to 100 microinches, and this roughness develops a correspondingly high amount of friction and heat between chip and tool. When the surface is polished to 5 microinches or less, the effect of friction is reduced to a degree that is truly remarkable. Actual tests of long duration have proved that the life of the tool edges may be extended by as much as 10 to 20 times over that obtainable with hand-ground tools. In large machine shops this type of improvement is well worth the small amount of extra time and equipment required to reduce tool roughness. There is no cutting oil made that will impart such an improvement. Another method which produces a similar result is to plate the tools with chromium and thereby fill in the imperfections with a hard smooth surface.

Chip Breakers

Another influential factor in many cutting operations is the action of chip breakers.

When chips are of the long curling type they are hard to handle as scrap, and in addition they appear to encourage the maintenance of a large and undesirable built-up edge, particularly when rough cutting some of the tough ferrous metals. If the tool is provided with a back wall or chip breaker, the chips are forced to break and the built-up edge is apparently subjected to shock waves which impart the beneficial effect of dislodging and reducing the size and influence of this fragmentary metal as it tends to anchor on the tool. The action of a chip breaker is shown in Fig. 2, where depths of ⅛ inch to ¼ inch from the cutting edge are suggested. This factor depends upon the size of the tool and depth of cut. As a general rule the larger the tool, the greater the distance of the chip breaker from the cutting edge.

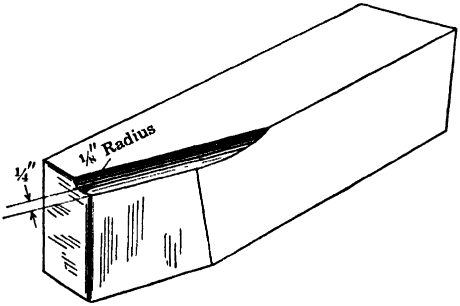

Fig. 2. Cutting tool with chip breaker.

Several reasons may be surmised for the longer tool life and better finish that are secured in many cutting operations with a chip breaker: the built-up edge is reduced in size, the pressure of the chip is distributed at points, there is no protracted period of contact between the hot chip and the tool, and the coolant has freer access to the bearing surfaces owing to less obstruction. Whatever the reasons, there is no doubt that in many applications the finish is just as good, and often better, than when the workpiece is machined without a chip breaker. Furthermore, the advantage of small chips from the viewpoint of commercial value and ease of handling is a consideration, especially when they can be produced without sacrifice to the cutting operation.

Tool Rakes

The common terms applied to cutting tools are illustrated in Fig. 3. Exaggerated hooks and rakes on cutting tools are very often the cause of rapid tool wear and excessive build-up on the edges. The greater the rake, the weaker the cutting section; and the greater the hook, the more the cutting tool resembles a razor blade. Figure 4 is an example of a tool showing both faults.

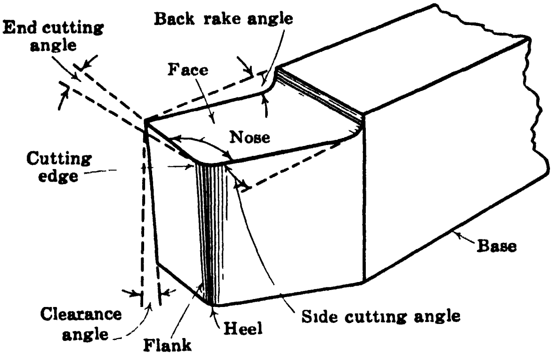

Fig. 3.

In all cutting operations on hard metals the tool rake should be as near to a right angle as possible, and hooks or back rakes should be reduced to a minimum. The grinding of fancy shapes and curves only serves to weaken the tool. This does not mean that all metals can be cut with 3° to 5° back rakes, but there is no need for many of the detrimental and imaginative tool shapes that are a common sight in machine shops. An artistic tool-grinding job does not extend its influence to the practical operation of cutting metal.

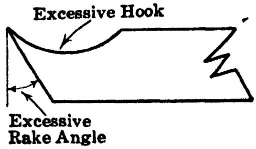

Fig. 4. Cutting tool with excessive hook and front rake.

No hard and fast rules can be made for tool rakes, but, generally speaking, the back rake should be 0 degrees or even negative for shock-load cutting operations. These shock loads occur on planing, shaping, and milling operations. For cutting soft metals such as aluminum and magnesium the back rakes may be 20 degrees for very high speeds and light feeds on turning operations.

Flow and Temperature of the Cutting Oil

The flow of the cutting fluid is an important factor that is not always recognized. The stream of oil or emulsion should not only be copious but should fall gently onto the tool and workpiece. When pressure is used on the stream or when the jet is located too far above the operation, an excessive splashing effect is produced which lowers the cooling action to a marked degree.

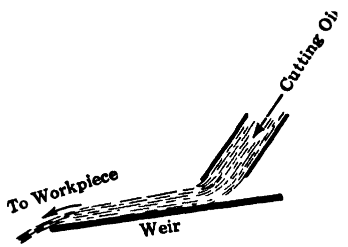

FIG. 5. Action of a weir to reduce splashing of the cutting oil as it flows to the workpiece.

In some operations involving large or broad cutting tools it will often be found advantageous to employ two or more streams of cutting oil flowing into strategic sections rather than one large stream. The action of a weir (Fig. 5) is highly advantageous with broaching, milling, and hobbing operations. However, in all cutting operations, an important factor is to direct a liberal flow of cool cutting oil close to the work. High waterfall effects and high efflux pressures cut down the supply of coolant to the cutting operation by maintaining a hosing or splashing action, which is detrimental and may "starve" the cutting tool.

The temperature of the cutting oil is also very important. If the system is not large enough to dissipate adaquately the heat in the oil, steps should be taken to enlarge the capacity or install cooling equipment. On close tolerance work flow and temperature of the cutting oil are even more important. In many cases oil coolers must be provided to maintain the oil and machine at a constant temperature.

Holding to Size

The following factors are among the most important in holding workpieces to size:

Build-up on the tool causes variations in size.
Excessive front rakes allow chattering.
Excessive hooks or back rakes tend to dig in.
Variations in oil temperature affect accurate work.

Tool holder should be close to workpiece; otherwise chattering and digging tend to cause variations in size.

Smooth contact surfaces for the flowing chip aid in holding to size and tend to prolong the life of the tool.

The cutting oil or emulsion should be maintained at a temperature that will keep the work as near room temperature as possible.

Central Systems for Distributing Cutting Oils and Emulsions

The central gravity flow or pressure supply method of distributing a cutting oil to batteries of machine tools has many advantages. This method of piping the oil or emulsion to and from each machine is not always practical, sometimes on account of the initial expense, the layout of the machines, or other physical considerations. However, the superiority of the central supply method may be likened to the advantage of turning on a faucet over drawing oil from a well and carting it around in buckets.

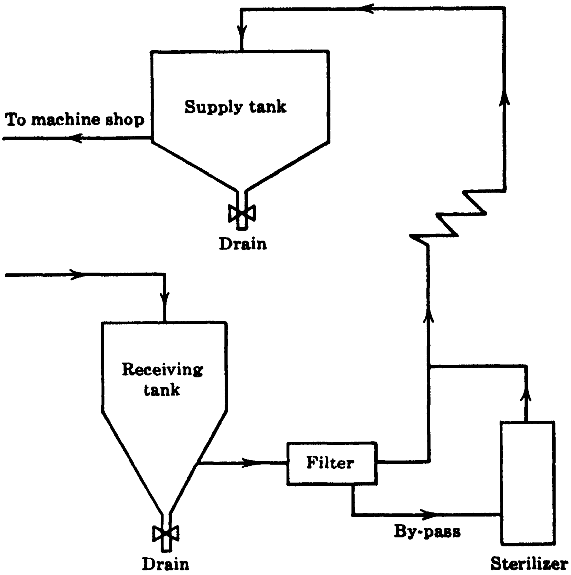

Fig. 6.

With a central supply system, the used oil or emulsion may be continuously filtered to remove fine chips or metal dust, etc., sterilized against the industrial hazard of harboring germs which cause skin eruptions (better known as dermatitis) and, of course, cooled to any desired temperature before being returned to the machines. This method is so obviously superior to the individual charge of cutting oil or emulsion in each machine that a further detailed discussion of its merits is hardly necessary.

Central supply systems are not difficult to install, and the mechanical equipment required is simple. The method is not used extensively but is worthy of more consideration because one cutting oil containing 0.6 to 1 per cent of added reactive material will generally cover the requirements of at least 50 per cent of the automatic tools and cutting operations in the average machine shop. For a battery of grinding machines, the emulsion is easily handled by a central system. Figure 6 shows the schematic layout of a central supply system for any type of cutting oil or emulsion.

Misting

Oil mist from machine tool operations may sometimes be a difficult matter to control. One effective cure is to shroud the cutting operation. Increasing the viscosity of the cutting oil will sometimes reduce the amount of mist, but this step will often interfere with the operation of the cutting tools.

Heavy oil mists around machine tools are an objectionable hazard to the health of everyone in the shop. Many cases of eye trouble, skin eruptions on the face, etc., have resulted from this source, and they should not be tolerated. One need only examine the composition of cutting oils to conclude that they are not desirable eye washes or face lotions.

Several methods may be employed to reduce or eliminate oil mist. The following are among the most common:

Increase the cutting oil capacity to maintain lower temperatures.
Install an oil-cooling unit.
Install shrouding.
Install electrostatic precipitators.

Electrostatic units consist of a sheet metal chamber located above the machine; the oil mist is drawn into this chamber by a fan and is then subjected to a potential of several thousand volts. This imparts a positive charge to the oil droplets, which are then attracted to negative plates, and from this point they run together and are drained back to the machine. The air passes out entirely free of oil.

Dual-Purpose Cutting Oils

Automatic screw machines and similar special machines are generally equipped with circulating oiling systems or mechanical lubricators to lubricate the many bearings, driving gears, cams, etc., which comprise the driving section. On machines with a number of spindles, it is often difficult to seal completely each spindle and prevent leakage of the machine oil into the cutting oil. If this leakage is sufficient to cause enough dilution to interfere with the cutting operation, the best practice is to use the cutting oil in the lubricating system. This can be done without any sacrifice to good lubrication because bearing and gear-tooth pressures in automatic machines are comparatively light, and, if the cutting oil has a Saybolt viscosity of 130 seconds at 100° F or above, there need be no fear of damaging the operating parts. (This reasoning applies to the great majority of automatics.) However, when carrying out the practice of using the cutting oil for a dual purpose, a necessary precaution is to use a base oil that is noncorrosive, as, for example, grades wherein the extreme-pressure element such as sulfur is properly combined with a fatty oil, or other suitable carrying medium, before it is blended with light mineral oil.

The practice of using the cutting oil for a dual purpose may tarnish bronze bushings, but this effect must not be confused with actual corrosion. The chemical reactions which produce tarnish and corrosion are similar, but very often there is a difference in the physical result. In this connection the copper strip test (Chapter 10) and other variations of this test are sometimes employed to throw suspicion on the practice of using suitable cutting oils as lubricants in automatic machines. However, these technical objections have no basis in fact (provided the cutting oil is not actually corrosive) because a slight tarnish on bronze bushings will do no harm. When the automatics are equipped with ball or roller bearings, there will not be even a trace of tarnish if the ingredients in the cutting oil are properly combined.

The copper strip test determines the presence of materials which cause tarnish or corrosion. In practice a polished copper strip is placed in a bath of the oil under test, and the temperature is maintained at 212° F for 3 hours. At the end of this period the copper strip is examined and its appearance reported as negative, slight discoloration, heavy discoloration, black, etc. The test is very simple, and the ideal result is, of course, negative.

This test does not identify the item or items which may be producing the tarnish or corrosive action, nor does it always indicate their possible degree of corrosiveness on other metals and alloys. However, it may be stated that all properly refined straight mineral oils will show a negative result, and compounded cutting oils should register no more than a very slight discoloration if they are to be used for lubricating bearings, gears, and cams, etc., on automatic machine tools. In this connection it is interesting to note that an almost microscopic percentage of free sulfur in any cutting oil will react on the strip. Furthermore, other types of compounds may be found which do not tarnish the strip to any noticeable extent, but they may form a minute quantity of metallic salt. This entire subject should be taken up with the supplier of the particular cutting oil rather than placing complete reliance on the copper strip test.

Occasionally special automatics are designed to operate under heavy bearing and gear pressures, but these machines are exceptions. Even so, the viscosity of the cutting oil can often be raised and a satisfactory compromise effected to satisfy both requirements. In this connection it is seldom necessary to raise the viscosity of the dual-purpose oil above 175 seconds at 100° (Saybolt).

Filtering, Sterilizing, and Testing

If a number of automatic screw machines are operated the loss of oil from the lubricating systems may be quite high. This oil enters the cutting oil systems, where much of it is carried away and lost by clinging to the chips, but very often this particular loss is not sufficient to balance the make-up that must be added to the lubricating systems. Consequently, an excess amount of used oil tends to accumulate over a period of time. If the chip loss just about equals the make-up it is a simple matter to add only new cutting oil to the lubricating systems, but, where the excess is appreciable, steps must be taken to filter the used oil so that it may be returned to the lubricating systems. This procedure requires careful consideration when selecting filtering equipment, as otherwise the used oil may cause operating difficulties in the bearings, gears, etc., by causing premature wear.

There are several ways in which used cutting oils may be filtered. One flexible and effective method is to run the oil through chip centrifuges, then *slowly* through a roomy tank equipped with size 600 mesh removable screens, then through a magnetic filter, then through an oil centrifuge or filter, then to vertical cone-shaped rest tanks equipped with heating coils to sterilize the oil against dermatitis bacteria and at the same time to thin the oil to a point where any remaining impurities will free themselves and sink to the bottom of the cone-shaped tanks. Figure 7 shows a schematic view of a complete system designed along these lines.

This type of system has the advantage of being simple to operate and maintain, and is just about foolproof. The screening tank and magnetic filter eliminate much of the rough material and incidentally aid in reducing wear and tear of the oil centrifuge, pumps, filter, etc.

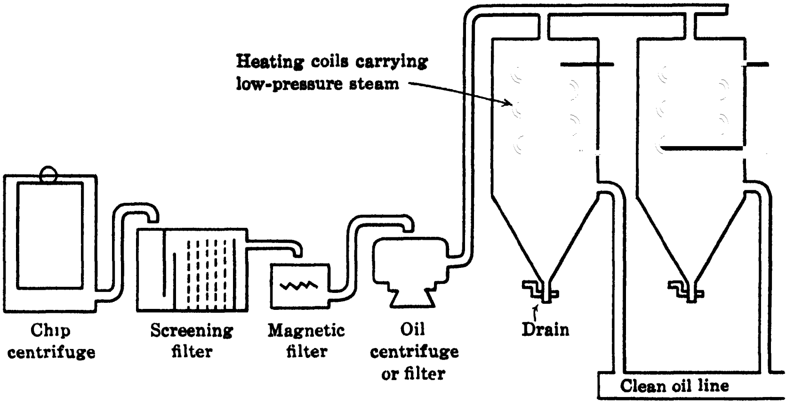

Fig. 7.

The heating coils in the rest tanks not only sterilize the oil, but they materially aid in freeing the oil from everything that has a higher specific gravity. The cone-shaped design collects these materials at one point where they can be drained off.

Sterilizing Cutting Oils

The oil in the rest tanks should be brought to a temperature between 150° F and 165° F, held there for about half an hour, and then allowed to cool and settle for at least 2 days. At the end of this period the oil will be sterile, and also free from the finest abrasive impurities. It is important that the heating operation be carried out below 180° F because excessive heating may tend to decompose the compounds in cutting oils and produce unnecessary and detrimental deposits. Furthermore, the oil must be allowed to rest for a sufficient period of time after the heat is shut off because it may take 24 hours for the circulating currents to die out in a large tank. This method of filtration is slow, but it is one of the surest and most effective known.

Testing for Abrasive Materials

The filtered oil should be tested for impurities by employing the ash test (Chapter 10). This procedure will disclose the presence of inorganic materials. However, this test generally requires experience to make correct interpretations, particularly if materials of an abrasive nature are found and require identification or if further steps have to be taken to assure their elimination.

Sometimes it is necessary to verify the materials in the ash, and this can be a painstaking task, but as a general rule the ash content is composed of metallic particles when applied to used cutting oils. When the cutting oil is new, there should be no ash content.

Fuller's earth, different types of diatomaceous earth, filtering clays, etc., are not generally suitable for purifying cutting oils because the fatty oil compounds tend to clog the tiny canals and surfaces of each particle rather rapidly, and the filtering medium becomes inoperative thereafter. However, clay-type percolating filters are very effective with straight mineral oils. Another rule to bear in mind, particularly when selecting filtering equipment of the centrifuge type, is to install large units and run the oil through at approximately half the rated capacity because centrifuges are much more effective if they are operated below their volumetric capacity. Before plans are made for a filtering process, the manufacturers of contemplated units should be consulted on these various points.

This discussion is a guide, rather than a specific recommendation, for solving the problem of filtering used cutting oils. There are several types of filters, sterilizers, and purifying combinations on the market which may be used effectively, but, regardless of the equipment employed, it is important to test the filtered oil at intervals and not to operate the system "blind" from year to year. A sloppy filtering operation can be very costly in repairs and renewals, particularly when using cutting oils for a dual purpose.

Skin Infections from Cutting Oils

Skin infections and irritations sometimes experienced among operators of machine tools are often attributed to the cutting fluid in use at the time. While little is known about this subject, it would appear from experience that a cutting oil in itself is seldom responsible for this condition. In most instances the source may be traced to one or more of the following causes:

1. Carelessness may permit small particles of metal in the cutting fluid to remain on the skin, resulting in irritation and possibly pus formations.
2. Germs or bacteria may be introduced into the cutting fluid by operators who have sores or skin diseases on their hands or arms or by men who expectorate into the fluid and who are carriers of germs, or who have throat infections or other health disorders.
3. The addition of excess quantities of alkali into soluble oil emulsions to prevent rusting is a source which may cause irritation and facilitate skin infections.
4. Another common cause of openings in the skin, permitting infection, is the use of kerosene for cleaning hands and arms. Kerosene washes the natural oils from the skin, causing a dry and chafed condition which results in cracks or openings, and thereafter germs have no difficulty in gaining entrance to the blood stream.
5. After cutting oils or emulsions have been used for a period of time, the fluids contain sharp metallic particles which are sufficiently small to enter the hair follicles of the skin. If not washed out, they may block the opening to the sebaceous glands, producing irritation and abrasions and a favorable environment for pus-forming bacteria.

Cleanliness of hands, arms, and working clothes is therefore an important single factor in eliminating the possibility of skin troubles. The liberal use of soap and water will prevent and very often clean up an epidemic of cutting oil infections. Machine operators should always wash their hands and arms with a neutral soap in warm water before quitting work for lunch or for the day, and care should be taken that the cuffs, as well as the collars, of their overalls, coats, or shirts are cleaned once a week. The latter is very important because any oil that remains on clothing for an appreciable period of time picks up dirt and dust. Continual rubbing of the skin on dirt-hardened clothes will cause skin eruptions, purely as a result of irritation, regardless of how neutral or harmless the oil may be.

The importance of preventing cutting oil infections has prompted several companies to develop additional protective means to supplement strict cleanliness. Hand creams have been developed which will materially protect the skin against the entrance of dirt, metal particles, oil, or chemicals.

The use of antiseptic compounds in the oil will aid in preventing the growth of bacteria. Many products used for this service have not proved very effective, but a few have been found highly beneficial, particularly when used in conjunction with heat sterilizers.

Batches of cutting oils may be sterilized every two weeks by heating to a temperature of 150° to 165° F for not less than half an hour. This method is laborious, but it is the most effective of all. At the same time the cutting oil should be filtered or centrifuged to remove the fine metal particles which tend to enter the skin of the operators.

It is sometimes claimed by users of cutting oils who have experienced skin troubles that the oils as received contain germs or bacteria. However, the temperatures to which oils are subjected in refining and blending are sufficiently high to preclude the presence of any living bacteria. Experience indicates that their presence and multiplication are due to their introduction by operators who are themselves infected. Hence it is very important that men who have skin infections or suspicious health disorders be kept away from cutting fluids to prevent spreading the infections to other operators. Sometimes a troublesome epidemic can be traced to one man.

Skin eruptions, or dermatitis, may sometimes affect predisposed persons when they come in continual contact with any oil, or even water. When a machine operator is found to be predisposed to skin troubles, he should be transferred to another department where he will not be required to handle irritative substances and infect others.

This discussion is not intended to replace the aid of expert medical advice. In the event of an outbreak of dermatitis, medical treatment is very important. At the same time, all machines suspected of containing germ-carrying oil should be cleaned out very thoroughly. In machine shops where no precautions are taken in cleanliness, dermatitis may strike at any time, regardless of the type of cutting oil or oils in use.

Reference

The United States Department of Health has published reports of investigations carried out to determine the cause and cure of industrial skin diseases. For further information apply to The National Institutes of Health, Bethesda, Maryland, U.S.A.

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Lubrication of Equipment

All mechanical equipment consists of well-recognized materials and mechanical motions, in endless combinations and for a variety of purposes. These mechanisms are used under many conditions. The hydraulic system used for control in an airplane can be held in the hand. The same mechanical principle operates huge presses that may stand 40 feet high. The aircraft's hydraulic mechanism may have a temperature operating range of −100 to 160° F, with a total operating life of a few hundred hours. The press's hydraulic system will generally operate from 50 to 100° F, with a life expectancy of thousands of hours. It is evident that to make specific lubrication recommendations for each machine and model and the conditions surrounding its use would require volumes of work and never be all-inclusive and up-to-date. It is therefore necessary to make an analysis of each machine's lubrication requirements with consideration of its duty and environment.

Lubrication Recommendations

In the industrial plant the lubrication engineer is called upon to lubricate everything from squeaky office chairs to all the production machines and parts. Lubrication surveys of each piece of equipment are necessary to ensure that the proper lubricants are applied to every moving part. They also provide a record of the lubricants required and serve as written information for all concerned.

In making the survey, the equipment manufacturer's lubrication recommendations should be noted. An analysis of this data will disclose that there is lack of agreement between machine builders and that an unmanageable number of types of lubricants would be required. This condition stems from the fact that most machine parts are not supercritical to reasonable viscosity changes.

The following example illustrates this point and lists reasons for the deviation from the recommended practice.

CONVEYER DRIVE

Unit	*Part*	*Manufacturer's Recommendation*	*Plant Recommendation*
Motor	2 ball bearings	Manufacturer's grease	Ball bearing grease [1]
Coupling	Lubricated	Grease	Still bottom [2]
Gear case	Herringbone	500 S.S.U. oil	800 S.S.U. oil [3]
Gear case	Spiral bevel	800 S.S.U. oil	800 S.S.U. oil
Gear case	Worm gears	Steam cylinder oil	800 S.S.U. oil [4]

[1] There are good ball bearing greases available which will lubricate 99% of the ball bearings, regardless of the type of equipment or its location. Occasionally a special grease is required for abnormally high or low temperatures or for bearings that may be subject to direct water wash, etc.

[2] We have mentioned that a grease is composed of soap and oil. As a coupling is a centrifuge, separation of the grease into soap and oil is most likely to occur. It is a certainty in large-diameter high-speed couplings. Therefore, a homogeneous lubricant should be used, as low in viscosity as can be retained by the seals.

[3] Herringbone, spiral bevel, and spur gears are not sensitive to viscosity. Extremely low-speed gears should have a high-viscosity oil, and high-speed gears a low-viscosity. The vast majority of industrial gears will operate with viscosities from 150 S.S.U. to 1500 S.S.U. at 100° F.

[4] It is assumed that this conveyor operates most of the time. The worm drive will not be subjected to frequent stops or shock loads. It will therefore operate on a low-viscosity oil in contrast to an elevator worm gear. It will be noted that it is easy to examine most worm drives through the filling plug and to check the used oil for metal.

Operating Conditions

The following survey will indicate how operating conditions affect the choice of lubricants.

PAPER MACHINE

Unit	*Part*	*Recommendation*
		Wet End
Wire	Ball bearings	Lithium, barium, or strontium grease [1]
	Plain bearings	Marine-engine oil [2]

[1] The regular soda soap grease is not recommended, since the excessive water wash would emulsify the grease and the lubricant would be washed away. The greases recommended have a preferential wetting for metal in the presence of water, and very infrequent greasing is required. If a calcium soap grease were used frequent greasing would be required, and the paper stock would be contaminated, owing to leakage of the grease. The initial cost of the grease recommended is higher than a cup grease, but the added cost is saved many times over because a smaller quantity is used and application time is shorter.

[2] The rapeseed compounding in a marine-engine oil forms an emulsion with the water which will lubricate better than a straight mineral oil. The emulsion, being water soluble, is carried away with the waste water, leaving clean machines and pipes.

PAPER MACHINE—*Continued*

Unit	*Part*	*Recommendation*
		Drier Section
Drum driers	Roller bearings	Circulating oil, turbine grade 500–1000 S.S.U.[3]
	Plain bearings	Turbine grade 500-1000 S.S.U. at 100° F
Felt rolls	Roller bearings	Ball-bearing grease[4]
Gear drive (open)	Spur gears	Still bottom 1000 S.S.U. at 210° F[5]
Steam joints	Plain bearings	Ball-bearing grease or sodium soap[6]
		Hydropulper
Gear drive	Hypoid or spiral bevel	Mild E.P. 300–800 S.S.U. at 100° F[7]

[3] Drum driers are heated with steam to temperatures that may reach 300° F or higher. The bearing operating temperatures may be as high as 180° F or higher. An oxidation-inhibited oil is called for, and this can be secured in a turbine grade.

[4] Felt roll bearings operate at temperatures of 140° F or higher. Once packed with an oxidation-inhibited grease, the bearings should operate 3 years or longer. Adding new grease to worn-out oxidized grease is false economy. When inspection indicates that additional or new grease is needed, the bearings should be cleaned and repacked with new lubricant.

[5] Oil, grease, or a still bottom can be used to lubricate open gears. Owing to the high ambient temperature and the centrifugal action, a heavy still bottom is recommended. This lubricant may even have to be heated to be applied, and yet it resists being "thrown" from the gear teeth, and to some extent resists removal by leaky steam joints. A small quantity added at frequent intervals is more advantageous than a liberal quantity at less frequent intervals.

[6] A soda soap grease will form an emulsion with the steam condensate, and lubricate well. Being water soluble, it leaves all surfaces clean. Water-insoluble greases would foul the system and interfere with heat transfer.

[7] When a bale of pulp is dumped into the hydropulper, a shock load is likely to occur in the drive. For this reason a mild E.P. lubricant is called for.

In chemical process equipment those parts coming in contact with the chemicals often require special lubricants. As an example, nitric acid may oxidize some lubricants so rapidly that fire occurs. For this reason it is imperative that the effect of the chemicals be studied before making recommendations. Many of the materials used as lubricants are not particularly good, and this is one of the reasons why chemical plant maintenance costs are high. Equipment manufacturers' recommendations and trade practices are often very helpful in providing recommendations.

Mechanical Conditions

The following survey will indicate how mechanical conditions dictate the choice of the lubricant.

PRECISION ROLL GRINDER

Unit	*Part*	*Recommendation*
Spindle	Sleeve bearings	45–65 S.S.U. at 100° F oil [1]
Ways	Plain surfaces	300 S.S.U. at 100° F mild E.P.[2]
Hydraulic drive	Pump and motor	150 S.S.U. at 100° F hydraulic or turbine-grade oil [3]

[1] The bearing clearances in precision spindles are so small that the operating temperatures must be kept lower than 20° F above room temperature. With these low temperatures oxidation characteristics are not important, but viscosity is all-important. The fluid friction of a high-viscosity oil will raise the temperature, expand the shaft, take up the clearances, and cause seizure.

[2] Ways, slides, and guides are parallel surfaces. As stated in Chapter 15, thick-film lubrication cannot be formed on parallel surfaces, no matter how copiously the oil is applied. Therefore, maximum wetting is required in the lubricant. This can be obtained from the polar compounds in the mild E.P. or way lubricant which is compounded for the same purpose.

[3] An additive type of oil is desired. It should contain an oxidation inhibitor to prevent varnish formation; an antifoam agent, as the rate of circulation is high; and a rust inhibitor, as moisture from condensation is present in closed systems.

Product Requirements

The choice of a lubricant is often governed to some extent by the product being manufactured. A few random examples will indicate some methods being employed.

The textile industry, to a large extent, employs almost colorless lubricants in many stages of their operation. In other stages water-soluble lubricants are used, so that they can be readily washed from the fabric. Lubricants must be carefully applied to avoid contamination. Semifluid greases are utilized on twister rings and other plain surfaces where leakage and spatter must be controlled.

The food, cosmetic, and pharmaceutical industries may require special lubricants, such as medicinal white oils, at certain stages of manufacture, or special procedures to prevent any chance of contamination.

Many of these white oil and special products have little lubricating value. Much more importance should be placed on the careful application of a lubricant than upon special lubricants in order to avoid difficulties. The oil man who relies entirely on special lubricants is very much like an ostrich that buries its head in the sand to shut out the view of oncoming trouble.

The requirements of the lubricant are not affected by the size of the equipment. The same lubricants will lubricate the smallest to the largest Diesel engine. The mechanism's lubricant requirement is the governing standard for the selection of the proper lubricant. Because the requirements are the same, a small helical gear case on an auxiliary turbine drive will use the same lubricant as a 14-foot-diameter gear on a ship propulsion drive.

A roll stand in a steel mill will require an E.P. lubricant that spreads well. The unit loading on the bearings may be about 2 or 3 tons per square inch. The same type of oil would not be used on the balance wheel bearing of a watch, where the loads may be 500 tons per square inch. In a watch an oil that spreads cannot be used, although an oil with E.P. properties is desirable. The requirements are further influenced by the fact that the steel shaft is supported by a jeweled bearing.

Lubricant Selection

Most progressive industrial plants provide the various types of lubricants to meet their requirements. Every attempt should be made to lubricate a new piece of equipment with lubricants already available. The effective application of this principle causes differences in the lubricant selection and application between any two plants. The following examples may be considered typical.

An air filter using oil to collect dirt from the air in a department store would more than likely be serviced with an air filter oil. The same filter installed in an industrial plant would use a 100 S.S.U. or 300 S.S.U. at 100° F straight mineral oil, depending on the type of filter. This oil would be taken from the normal stock in the plant.

Large volumes of mild E.P. oils are used in the steel industry for gear lubrication. These lubricants should therefore be utilized by most gear cases in the plant. Light industries have little or no need of E.P. lubricants and therefore should determine if an E.P. is needed before introducing one into the plant.

The oil selected for circulating systems is often governed by the major use for such an oil. Turbine-grade oils can also be used in ring oil bearings, most gear cases, hydraulic systems, etc., where little make-up oil is added. Hydraulic oils may be used for the same purposes, except for major turbine units, and it is questionable if even this is a limitation.

These illustrations point out that many oils have the desired properties for a given situation, and in many applications all the properties of the lubricant may not be needed. As long as the major requirements are met, the other properties can do no harm.

Lubrication Schedules

A lubrication schedule should be provided for all equipment to ensure that the proper lubricants are applied in the required quantities and frequencies.

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Lubrication Engineering

Lubrication engineering is a science that requires a knowledge of lubricants, materials, chemistry, machine design, maintenance practices, and control systems, to mention just a few. The perusal of the subjects briefly touched upon here should stimulate further study. There are many subjects connected with lubrication which have not been developed in this book. Only by constant study and experience will the lubrication engineer gain his job knowledge.

The fullest advantages of lubrication engineering will be found where an organized program is developed to meet the needs of an individual plant. The following suggestions will indicate some functions which will aid in putting this program into effect.

Lubrication Surveys

Lubrication surveys are necessary to determine the equipment in a plant that requires lubrication. The survey should also show what lubricants are being applied, the frequency of application, the method of application, the condition of the machinery, and any other general observations pertaining to the equipment.

Table 1 indicates the type of information needed to compile the plant-wide report and obtain the facts concerning lubrication.

Lubrication Specifications

Specifications are necessary for the control of materials. It is most difficult to write quality into lubricant specifications. The specifications should indicate the types of lubricants required, and the quality of each type is the responsibility of the supplier. As an example, the survey of a plant might indicate that ten products are required. They could be specified by comparable brands or simple specifications. Table 2 is an example of this procedure.

TABLE 1. PUNCH PRESS

Equipment	*Part*	*Lubricant*	*Method*	*Frequency*	*Proposed*		*Observations*
					Lubricant	*Frequency*	
Motor	2 ball bearings	Cup grease	Grease cup	Weekly	Ball bearing grease	Once 5 years	1
Crankshaft	2 plain bearings	Brand A	Hand	Hourly	300 S.S.U. squirt can	Weekly	2
Connecting rod	1 plain bearings	Brand A	Hand	Hourly	300 S.S.U. squirt can	Weekly	3
Clutch	Plain bearings	Brand B	Bath	As necessary	300 S.S.U. squirt can	Weekly	4
Ram	Plain bearings	Brand C	Hand	Every 4 hours	300 S.S.U. squirt can	Weekly	5

[1] Motor windings greasy and dirty. Clean motor and bearings, remove grease cups, and put in pipe plugs. Pack one-third full of ball-bearing grease and add small quantity every 5 years.

[2] Oil all parts of press with 300 S.S.U. squirt can oil. Replace hand oiling with wick-feed cups and fill once per week.

[3] Mount wick cup on bracket and connect to bearing with flexible tubing.

[4] Considerable grit and dirt in the well of the flywheel. Clean and renew the felt. Examine for dirt each month.

[5] Install wick-feed cups.

General Observations

Equipment being lubricated by operators. Considerable oil on product and floor. Some guards missing and others loose. Recommend that one man be assigned lubricating and clean-up. On large inaccessible presses consider automatic lubrication systems.

TABLE 2

Lubricant	*Viscosity at 100° F*	*Type*	*Pour Point*	*General Uses*	*Vendor*		
					1	*2*	*3*
1. Squirt can oil	280–320	Nonadditive		Hand oiling, punch presses, machine tools, ring oil bearings	Brand A	Brand B	Brand C
2. Circulating oil	280–320	R & O		Gear cases, etc.	Brand D	Brand E	Brand F
3. Hydraulic light	140–160	R & O		Piston-type pumps, high-speed ring oil bearings	Brand G	Brand H	Brand I
4. Hydraulic heavy	450–600	R & O		Vane-type pumps, drum drier bearings	Brand J	Brand K	Brand L
5. Cylinder oil	145–165 at 210° F	4–6% tallow		Engines on 260 lb steam, worm gears	Brand M	Brand N	Brand O
6. Diesel engine	S.A.E. 30	H.D.			Brand P	Brand Q	Brand R
7. Soluble cutting oil		Sulfonated		Grinding	Brand S	Brand T	Brand U
8. Base-cutting oil	When cut back with paraffin oil to be approx. 150 S.S.U.	2% lard, 2% sulfur, or equal			Brand V	Brand W	Brand X
9. Paraffin oil	90–110	Nonadditive (can be naphthenic)		Cut-back base oil, spindle oil	Brand AA	Brand BB	Brand CC
10. Refrigeration oil	140–200		−25° F	Low-temperature lubrication	Brand AX	Brand BX	Brand CX

In the early stages of the program the technical knowledge available within the oil industry should be utilized. This knowledge should not be called upon promiscuously, as it involves considerable time and expense. As knowledge is gained and the program expands, additional sources of information can be sought. It is best not to have a lubrication program based on a single source of supply. Reasonable competition is the wellspring of progress.

The purchasing department will play an active part in determining the sources of supply. It is the responsibility of the lubrication engineer to advise the purchasing department as to the value of the products being purchased. Every effort should be made to obtain the maximum value for monies spent. In some cases lower-priced lubricants will give equivalent service, and in other cases increasing the cost of the lubricant will be money well spent. The motor in Table 1 is a good example. The cup grease at 10 cents per pound required weekly application and contaminated the motor. A ball-bearing grease at two to three times the price needed to be applied only every 5 years.

Quality Control

Suitable tests should be run, depending on the volume and use of lubricants. These tests were outlined in Chapters 10 and 11, "Physical Tests" and "Functional Tests." These tests should be used to ensure that the proper types of lubricants are being supplied. Errors occur through misbranding, refining control, blending control, etc. Also, there is sometimes misunderstanding as to what is wanted. There is no advantage in controlling quality unless the lubricants are kept free of contaminates in dispensing and applying.

Inventory Control

A control over inventory should be exercised to ensure that the proper lubricants will be available at all times. Although lubricants are not perishable, it is advisable that they move continuously; especially is this true for greases.

Specialties and small-quantity lubricants should be eliminated at every opportunity. Periodic review of purchases and inventories will disclose any deviations from standard practices. A study of the dispensing records will disclose unusual lubricant requirements. These should be investigated for such matters as waste, need for filters, lubrication devices, and change in type of lubricant.

Lubrication Performance

The selection and application of lubricants is invariably governed by opinions, propaganda, and personal experience. Opinions and propaganda are of little worth, and the value of personal experience depends upon the accuracy of the observations. It is of utmost importance that all the factors governing lubrication be considered in determining the performance of a lubricant. A written record should be kept on observations and results, and actual figures used in place of generalities. Table 3 is an example of substituting actual facts for generalities.

TABLE 3

Generalities	*Actualities*
1. Sleeve bearing	1. 4″ × 6″ center ring oil bearing
2. Babbitt	2. High-lead Babbitt—6% tin
3. High temperature	3. 143° F
4. Small oil capacity	4. 8½ oz
5. High speed	5. 3600 surface fpm
6. Heavy load	6. 250 psi
7. Dirty conditions	7. Subject to paper dust
8. Length of service 8 years	8. Actual service 20,000 operating hours (2½ operating years)
9. Believed long life	9. Poor performance based on actual operating hours
10. Infrequent oil change—yearly	10. Frequent oil changes based on operating hours
11. Bad sludged deposits from oil	11. Deposits consist of paper dust
12. Electric motor	12. 150 hp, 3600 rpm, enclosed, 40° C temperature rise, 440-volt electric motor
13. Cold location	13. Normal room temperature 40° F

In addition to the facts outlined in Table 3, the physical conditions and the mechanical design must be carefully analyzed. A complete analysis of a truck transmission failure disclosed the fact that a thrust bearing had been omitted when the truck was assembled. As it required 18,000 miles for this failure to occur, it was thought to be a lubricant failure before a careful analysis was made.

Opinions of the success of any lubricant's performance should be reserved until sufficient time has elapsed to develop supporting data and facts. A given lubricant must operate under a variety of conditions, and no single field test can be used for conclusive data. The limitations of all lubricants must be reasonably well determined.

As an example, a ball-bearing grease, brand X, works well in ball bearings up to 2000 sfm under a variety of temperature and moisture conditions. This same grease failed completely when bearing speeds were above 3000 sfm. The cost of obtaining this lubrication performance data was negligible as compared to its widespread use on the basis of the data at 2000 sfm. This type of information enables the lubrication engineer to apply lubricants only to those places where they show good performance.

Money spent in finding the limitation of lubricants should be considered as research and development work. Failures should not deter a development program as long as progress is being made.

Lubrication Design

Lubrication engineers should be able to offer constructive suggestions for the adequate lubrication of moving parts. Table 4 lists a few of the countless number of points which should be considered in lubrication design.

TABLE 4

1. Is it possible to lubricate the mechanism?
2. Is there a lubricant available for the type of service?
3. Is there a suitable means or device for applying the lubricant?
4. Will the lubricant be contained, or will it spatter on the floor, operator, or product?
5. Have adequate seals and housings been provided to contain the lubricant?
6. Is the seal design such that it can be serviced?
7. Are lubricating devices, drain plugs, filling plugs, etc., accessible and of adequate size?
8. Are the materials of construction easy to lubricate, as is cast iron, or difficult, as stainless steel?
9. Are the tolerances and finishes correct for the service conditions?
10. Has the proper consideration been made for the expansion and contraction of machine parts?
11. Has the proper choice been made between "antifriction" and sleeve bearings?
12. What is the estimated cost for maintaining and applying the lubricant for a year?
13. Will a higher capital investment resulting in improved lubrication be justified?

Lubrication Training

Lubrication engineering is not generally included in formal engineering courses. This education may be obtained in several ways. Some schools offer special basic lubrication courses. Most engineers acquire lubrication knowledge through a course of study, experience, consultation with other lubrication engineers, and participation in technical societies and meetings.

This knowledge of itself is of little value until put into useful practice. The success of any lubrication program depends on the help of all persons who design, operate, or maintain mechanical equipment. In order to obtain the maximum benefits of the lubrication program, each group should have the lubrication information that is of interest to them.

A large part of a lubrication engineer's time is spent in training and educating people to effectively carry out his program. Lubrication is a dynamic science, requiring constant devotion to training for the improvement of lubrication practices.

TEMPERATURE CONVERSION TABLE

Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade
−5	−20.55	57	13.88	119	48.33	181	82.77	243	117.22
−4	−20.00	58	14.44	120	48.88	182	83.33	244	117.77
−3	−19.44	59	15.00	121	49.44	183	83.88	245	118.33
−2	−18.88	60	15.55	122	50.00	184	84.44	246	118.88
−1	−18.33	61	16.11	123	50.55	185	85.00	247	119.44
Zero	−17.77	62	16.66	124	51.11	186	85.55	248	120.00
+1	−17.22	63	17.22	125	51.66	187	86.11	249	120.55
2	−16.66	64	17.77	126	52.22	188	86.66	250	121.11
3	−16.11	65	18.33	127	52.77	189	87.22	251	121.66
4	−15.55	66	18.88	128	53.55	190	87.77	252	122.22
5	−15.00	67	19.44	129	53.88	191	88.33	253	122.77
6	−14.44	68	20.00	130	54.44	192	88.88	254	123.33
7	−13.88	69	20.55	131	55.00	193	89.44	255	123.88
8	−13.33	70	21.11	132	55.55	194	90.00	256	124.44
9	−12.77	71	21.66	133	56.11	195	90.55	257	125.00
10	−12.22	72	22.22	134	56.66	196	91.11	258	125.55
11	−11.66	73	22.77	135	57.22	197	91.66	259	126.11
12	−11.11	74	23.33	136	57.77	198	92.22	260	126.66
13	−10.55	75	23.88	137	58.33	199	92.77	261	127.22
14	−10.00	76	24.44	138	58.88	200	93.33	262	127.77
15	− 9.44	77	25.00	139	59.44	201	93.88	263	128.33
16	− 8.88	78	25.55	140	60.00	202	94.44	264	128.88
17	− 8.33	79	26.11	141	60.55	203	95.00	265	129.44
18	− 7.77	80	26.66	142	61.11	204	95.55	266	130.00
19	− 7.22	81	27.22	143	61.66	205	96.11	267	130.55
20	− 6.66	82	27.77	144	62.22	206	96.66	268	131.11
21	− 6.11	83	28.33	145	62.77	207	97.22	269	131.66
22	− 5.55	84	28.88	146	63.33	208	97.77	270	132.22
23	− 5.00	85	29.44	147	63.88	209	98.33	271	132.77
24	− 4.44	86	30.00	148	64.44	210	98.88	272	133.33
25	− 3.88	87	30.55	149	65.00	211	99.44	273	133.88
26	− 3.33	88	31.11	150	65.55	212	100.00	274	134.44
27	− 2.77	89	31.66	151	66.11	213	100.55	275	135.00
28	− 2.22	90	32.22	152	66.66	214	101.11	276	135.55
29	− 1.66	91	32.77	153	67.22	215	101.66	277	136.11
30	− 1.11	92	33.33	154	67.77	216	102.22	278	136.66
31	− 0.55	93	33.88	155	68.33	217	102.77	279	137.22
32	Zero	94	34.44	156	68.88	218	103.33	280	137.77
33	+ 0.55	95	35.00	157	69.44	219	103.88	281	138.33
34	1.11	96	35.55	158	70.00	220	104.44	282	138.88
35	1.66	97	36.11	159	70.55	221	105.00	283	139.44
36	2.22	98	36.66	160	71.11	222	105.55	284	140.00
37	2.77	99	37.22	161	71.66	223	106.11	285	140.55
38	3.33	100	37.77	162	72.22	224	106.66	286	141.11
39	3.88	101	38.33	163	72.77	225	107.22	287	141.66
40	4.44	102	38.88	164	73.33	226	107.77	288	142.22
41	5.00	103	39.44	165	73.88	227	108.33	289	142.77
42	5.55	104	40.00	166	74.44	228	108.88	290	143.33
43	6.11	105	40.55	167	75.00	229	109.44	291	143.88
44	6.66	106	41.11	168	75.55	230	110.00	292	144.44
45	7.22	107	41.66	169	76.11	231	110.55	293	145.00
46	7.77	108	42.22	170	76.66	232	111.11	294	145.55

Degrees centigrade (° C) × 1.8 + 32 = degrees fahrenheit (° F).
Degrees fahrenheit (° F) − 32 ÷ 1.8 = degrees centigrade (° C).
Absolute zero = −273.1° C = −459.58° F.

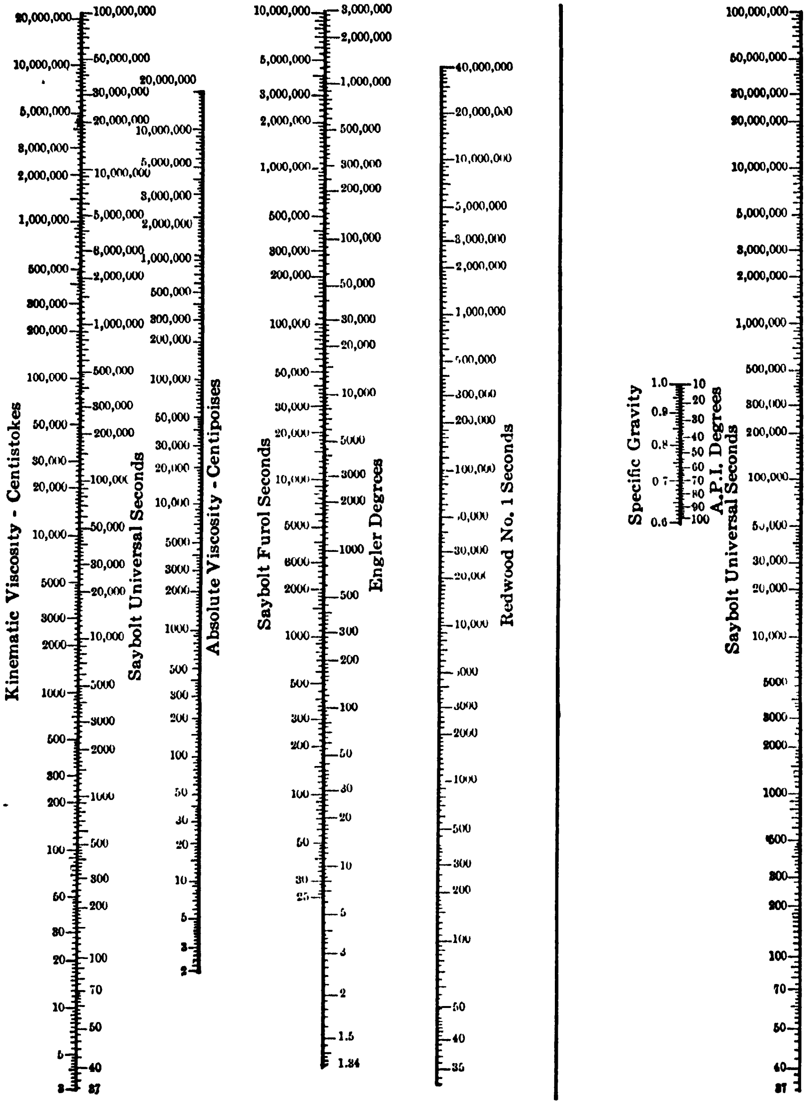
Temperature Conversion Table (*Continued*)

Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade	Fahrenheit	Centigrade
47	8.33	109	42.77	171	77.22	233	111.66	295	146.11
48	8.88	110	43.33	172	77.77	234	112.22	296	146.66
49	9.44	111	43.88	173	78.33	235	112.77	297	147.22
50	10.00	112	44.44	174	78.88	236	113.33	298	147.77
51	10.55	113	45.00	175	79.44	237	113.88	299	148.33
52	11.11	114	45.55	176	80.00	238	114.44	300	148.88
53	11.66	115	46.11	177	80.55	239	115.00	400	204.44
54	12.22	116	46.66	178	81.11	240	115.55	600	315.55
55	12.77	117	47.22	179	81.66	241	116.11	800	433.33
56	13.33	118	47.77	180	82.22	242	116.66	1000	537.77

Degrees centigrade (° C) × 1.8 + 32 = degrees fahrenheit (° F).
Degrees fahrenheit (° F) − 32 ÷ 1.8 = degrees centigrade (° C).
Absolute zero = −273.1° C = −459.58° F.

VISCOSITY CONVERSION TABLE

[To locate an equivalent reading use a straight edge. The desired conversion is directly across.]



GRAVITY CONVERSION AND WEIGHT TABLE

A.P.I. Gravity	Specific Gravity $\frac{60°}{60°}$ F	Weight per Gallon			
		American (U. S.)		British (Imperial)	
		Pounds	Kilos	Pounds	Kilos
10	1.000	8.328	3.778	9.996	4.534
11	.9930	8.270	3.751	9.926	4.502
12	.9861	8.212	3.725	9.857	4.471
13	.9792	8.155	3.699	9.788	4.404
14	.9725	8.099	3.674	9.721	4.409
15	.9659	8.044	3.649	9.655	4.379
16	.9593	7.989	3.624	9.589	4.350
17	.9529	7.935	3.599	9.524	4.320
18	.9465	7.882	3.575	9.461	4.291
19	.9402	7.830	3.552	9.398	4.261
20	.9340	7.778	3.528	9.336	4.235
21	.9279	7.727	3.505	9.275	4.207
22	.9218	7.676	3.482	9.214	4.179
23	.9159	7.627	3.460	9.155	4.153
24	.9100	7.578	3.437	9.096	4.126
25	.9042	7.529	3.415	9.037	4.099
26	.8984	7.481	3.393	8.979	4.073
27	.8927	7.434	3.372	8.923	4.047
28	.8871	7.387	3.351	8.867	4.022
29	.8816	7.341	3.330	8.811	3.997
30	.8762	7.296	3.309	8.757	3.972
31	.8708	7.251	3.289	8.703	3.948
32	.8654	7.206	3.269	8.649	3.923
33	.8602	7.163	3.249	8.598	3.900
34	.8550	7.119	3.229	8.545	3.876
35	.8498	7.076	3.210	8.493	3.852
36	.8448	7.034	3.191	8.443	3.830
37	.8398	6.993	3.172	8.394	3.807
38	.8348	6.951	3.153	8.343	3.784
39	.8299	6.910	3.134	8.294	3.762
40	.8251	6.870	3.116	8.246	3.740
41	.8203	6.830	3.098	8.198	3.719
42	.8155	6.790	3.080	8.150	3.697
43	.8109	6.752	3.063	8.104	3.676
44	.8063	6.713	3.045	8.058	3.655
45	.8017	6.675	3.028	8.012	3.634
46	.7972	6.637	3.011	7.966	3.613
47	.7927	6.600	2.994	7.922	3.593
48	.7883	6.563	2.977	7.878	3.573
49	.7839	6.526	2.960	7.833	3.553
50	.7796	6.490	2.944	7.790	3.534
51	.7753	6.455	2.928	7.748	3.514
52	.7711	6.420	2.912	7.706	3.495
53	.7669	6.385	2.896	7.664	3.476
54	.7628	6.350	2.880	7.622	3.457
55	.7587	6.316	2.865	7.581	3.439
56	.7547	6.283	2.850	7.541	3.421
57	.7507	6.249	2.835	7.501	3.402
58	.7467	6.216	2.820	7.461	3.384
59	.7428	6.184	2.805	7.423	3.367
60	.7389	6.151	2.790	7.383	3.349
61	.7351	6.119	2.776	7.345	3.332
62	.7313	6.087	2.761	7.306	3.314
63	.7275	6.056	2.747	7.269	3.297
64	.7238	6.025	2.733	7.232	3.280
65	.7201	5.994	2.719	7.195	3.264
66	.7165	5.964	2.705	7.159	3.247
67	.7128	5.934	2.692	7.123	3.231
68	.7093	5.904	2.678	7.087	3.215
69	.7057	5.874	2.664	7.051	3.198
70	.7022	5.845	2.651	7.016	3.182
71	.6988	5.817	2.639	6.982	3.167
72	.6953	5.788	2.625	6.947	3.151
73	.6919	5.759	2.612	6.913	3.136
74	.6886	5.731	2.600	6.879	3.120
75	.6852	5.703	2.587	6.845	3.105

Metric and British (and American) Equivalent Measures

Length

Metric	*British and U. S.*
1 meter (m)	= 39.37 in., or 3.280833 ft, or 1.093611 yd
0.3048 meter (m)	= 1 foot
1 centimeter (cm)	= 0.3937 inch
2.54 centimeters (cm)	= 1 inch
1 millimeter (mm)	= 0.03937 in., or 1/25 in., nearly
25.4 millimeters (mm)	= 1 in.
1 kilometer (km)	= 1093.61 yd, or 0.621369 mile

Surface

1 square meter (sq m)	= 10.76387 sq ft = 1.1998 sq yd
0.8361 square meter	= 1 sq yd
0.0929 square meter	= 1 sq ft
1 square centimeter (sq cm)	= 0.15500 sq in.
6.452 square centimeters	= 1 sq in.
1 square millimeter (sq mm)	= 0.00155 sq in. = 1973.5 circ mils
645.2 square millimeters	= 1 sq in.
1 are = 100 sq meter	= 1076.41 sq ft
1 hectare = 100 ares	= 107641 sq ft = 2.4711 acres
1 sq kilometer (sq km)	= 0.386109 sq mile = 247.22 acres

Volume

1 cubic meter (cu m)	= 35.314 cu ft = 1.308 cu yd
0.7645 cubic meter	= 1 cu yd
0.02832 cubic meter	= 1 cu ft
1 cubic decimeter (cu dm)	= 61.0234 cu in. = 0.035314 cu ft
28.32 cubic decimeters	= 1 cu ft
1 cubic centimeter (cc)	= 0.061 cu in.
16.387 cubic centimeters	= 1 cu in.
1 cubic centimeter = 1 milliliter	= 0.061 cu in.
1 deciliter	= 6.102 cu in.
1 liter (lr.) = 1 cubic decimeter	= 61.0234 cu in. = 1.05671 quarts, U. S.
1 hectoliter or decistere	= 3.5314 cu ft = 2.8375 bu, U. S.
1 stere, kiloliter, or cubic meter	= 1.308 cu yd = 28.37 bu, U. S.

Capacity

1 liter (= 1 cubic decimeter)	= 61.0234 cu in. = 0.03531 cu ft = 0.2642 gal (American) = 2.202 lb water at 62° F
28.317 liters	= 1 cu ft
4.543 liters	= 1 gal (British)
3.785 liters	= 1 gal (American)

Weight

1 gram (gm) = 15.432 grains
0.0648 gram = 1 grain
1 kilogram (kg) = 2.204622 pounds
0 4536 kilogram = 1 pound
1 tonne or metric ton = 0.9842 ton of 2240 pounds
1000 kilograms = 2204.6 pounds
1 016 metric tons = 1 ton of 2240 pounds

Metric and British Equivalents of Compound Units

1 kilogram per square centimeter = 14.223 lb per sq in.
1.0335 kg per sq cm = 1 atmosphere = 14.7 lb per sq in.
0.070308 kilogram per square centimeter = 1 lb per sq in.
1 kilogram-meter = 7.2330 ft-lb
1 force de cheval = 75 kg-meter per sec = 0.9863 hp

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